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REPORT**

Using the CERL Pipe Loop System (PLS) To Evaluate Corrosion Inhibitors That Can Reduce Lead in Drinking Water

by
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Army Directorates of Engineering and Housing (DEHs) and managers of water utilities must comply with new Federal requirements to reduce copper and lead in drinking water. Because lead and copper are present in water systems as by-products of corrosion, one way to reduce their levels is to control corrosion by adding chemicals that will form a protective scale lining on the plumbing materials.

DEHs and utility managers find it difficult to assess distribution systems because the piping usually is inaccessible. They need a reliable method of assessing both the system's condition and the effect of corrosion control additives.

A literature review provided information on corrosion inhibitors and case studies conducted to determine corrosion sources and treatment options. The CERL-PLS was then used to determine and compare the effectiveness of three zinc orthophosphate and one bimetallic zinc polyphosphate corrosion inhibitors in tap water. The demonstration also determined the effectiveness of the CERL-PLS in evaluating corrosion inhibitors.

All four chemical corrosion inhibitors were effective in controlling corrosion. It is recommended that the CERL-PLS be considered for use by all installations to monitor the effects of water quality on the distribution system and to help evaluate corrosion control alternatives.

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FOREWORD

2

CONTENTS

TABLES

FIGURES

FIGURES (Cont'd)

USING THE CERL PIPE LOOP SYSTEM (PLS) TO EVALUATE CORROSION INHIBITORS THAT CAN REDUCE LEAD IN DRINKING WATER

1 INTRODUCTION

Background

A water distribution system represents a major investment for an Army installation, just as it does for a water utility. The installation Directorate of Engineering and Housing (DEH) or Directorate of Public Works (DPW) is responsible for ensuring that the local system is properly maintained and that it carries adequate amounts of properly treated, safe potable water. However, it is difficult to evaluate the system's condition or the effect of water quality on the system because it usually is inaccessible. The reenacted Safe Drinking Water Act (1988) requires evaluation of the corrosive effects of product water on pipe materials.

To help meet these requirements, the U.S. Army Construction Engineering Research Laboratories (USACERL) developed the CERL pipe loop system (CERL-PLS), a multipurpose, inexpensive, easy-to-use evaluation tool. The pipe loop system can be used for simple visual observations of water quality or a complete identification of corrosive characteristics of water on various pipe materials. It provides a basis for evaluating several corrosion control techniques including material selection and modification of water quality by water treatment chemicals. Internal corrosion control in water distribution systems has direct benefits for consumers in terms of economics, aesthetics, and health.

The pipe loop system was first introduced by USACERL in *Development of the Pipe Loop System for Determining Effectiveness of Corrosion Control Chemicals in Potable Water Systems* (Prakash et al. 1988). As the product became more widely used, other research reports followed: *Drinking Water Treatment Optimization Using the Pipe-Loop System: Demonstration at Aberdeen Proving Ground* (Temkar, Scholze, and Smith, 1990) and *Lead Monitoring Strategies for Drinking Water Systems - Lessons Learned* (Temkar et al. 1991), which focus on using the CERL-PLS to meet regulatory and corrosion control requirements. The system has been used successfully at Forts Monroe, Bragg, Hood, Ord, Irwin, and Lewis; Aberdeen Proving Ground; Picatinny Arsenal; Sunflower Army Ammunition Plant, and also in the municipal sector in New York, NY, and Philadelphia, PA. The CERL-PLS has been published as a standard by the American Society for Testing and Materials (ASTM, D2688-90). A *User Guide for the USACERL Pipe Loop System* (Scholze 1993) has been published.

Federal requirements to minimize lead and copper in drinking water, proposed on August 18, 1988 and promulgated on June 7, 1991, affect all military and community water systems, regardless of size. The regulations mandate both optimal corrosion control to minimize lead and copper as corrosion by-products and a public education program so consumers can reduce exposure. System treatment would be triggered by various "action levels." If the quality of a contaminant is below the "action level," no action would be required. According to the U.S. Environmental Protection Agency (USEPA), a treatment technique initiated immediately upon analysis of tap-water samples with lead levels exceeding an "action level" would best protect the public health.

The complexity of chemical interactions and the lack of both fundamental and applied corrosion control research dictate that treatments now being considered in water plants be based on individual systems. Because of the potential for serious health consequences when lead solubility control

deteriorates, a comprehensive monitoring program based on intelligent sampling, targeted at the worst cases, must be in place in the system before treatment changes are made. Monitoring will then establish a baseline for comparison and to assure future treatment effectiveness.

Pilot-plant scale tests and pipe loop studies could indicate the effectiveness of inhibitor dosages and water quality adjustments before they are actually introduced into the system. Previous pipe loop studies to predict lead levels have used coupons and pipe inserts made of lead and copper. Assessing the effect of different treatment schemes on lead leaching from solder joints in copper tubing has been a problem. A correlation between the behavior of actual lead/tin soldered joints in pipe and pure lead/tin solder applied to coupons or pipe inserts has not been established. Factors affecting the correlation include the amount of lead exposed inside the pipe (which is impossible to determine without dismantling the pipe) and the ability to reproduce the joint construction. Another problem is the apparent aging effect on the solder as lead is removed and films are formed; new solder will undoubtedly give a more pessimistic assessment of lead corrosion control than would be the case with truly representative older joints.

The most common treatment for corrosion control is lime softening, which is based on maintaining a positive value of the Langelier Index (LI). A positive LI theoretically indicates the water is saturated with calcium. As the water tries to achieve equilibrium, calcium will be precipitated out of solution in the form of calcium carbonate ($CaCO_3$). This precipitate should form a protective scale lining on the plumbing material. It is this protective lining that minimizes corrosion by preventing the water from contacting the plumbing materials. Unfortunately, maintaining a positive LI does not always ensure that a protective lining is formed throughout the entire distribution system. It would be most beneficial to develop a simple testing procedure to determine the corrosion potential of a distribution system.

Objective

The objective of this research was to demonstrate how the CERL-PLS evaluates the effectiveness of various chemical corrosion inhibitors in a water distribution system.

Approach

Researchers conducted a review of literature pertaining to corrosion control in water distribution systems. The review included pertinent regulations, related health publications, documentation on monitoring and treatment processes, chemical information on corrosion inhibitors, and case studies. Researchers then conducted a battery of experiments to evaluate the effectiveness of four corrosion control chemicals.

This report includes an investigation of the experience at the Rend Lake Conservation District Intercity Water Treatment Plant in determining effective control of lead dissolution into the drinking water supply. Rend Lake, in southern Illinois, was selected as the test site because it is similar to a typical Army installation water utility. The district is a water wholesaler that provides water to many of the small towns in the area. The plant produces an average of 12 million gallons* per day. The only corrosion control treatment that is used by the plant is lime softening.

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*A metric conversion table is on page 48.

Mode of Technology Transfer

It is recommended that information in this report be incorporated in revisions to Technical Manual (TM) 5-813-1, *Water Supply: General Considerations*, and TM 5-660, *Maintenance and Operation of Water Supply Treatment and Distribution Systems*. It is also recommended that a Public Works Technical Bulletin be published. A Facilities Engineering Applications Program (FEAP) user guide is now available.

2   LITERATURE REVIEW

This section contains a brief history of lead regulations in the United States, information on the health effects of lead, and a description of monitoring and treatment requirements for lead in drinking water. This is followed by a review of the use of various chemical corrosion inhibitors and corresponding case studies on the use of chemical inhibitors in waterworks distribution systems.

Lead and Its Health Effects

Lead is a soft, dull grey metallic element that is a relatively minor constituent of the earth's crust but is widely distributed in low concentrations in sedimentary rock and soil.

Damage to health caused by the total amount of lead in the body is usually related to the blood level measurements. No consistent level of safety has been detected. Blood levels of lead above 25 to 30 micrograms per deciliter (µg/dL) have been associated with definite adverse health effects in children. Levels of 10 to 15 µg/dL and above are associated with some risks that can collectively be considered adverse health effects in children.

Ingesting high levels of lead , _n cause physical damage resulting in severe illness. Lead has no useful purpose in the body, and can be toxic. Most ingested lead is ex..icted, but some residual amount remains in the body. Concentrations of lead accumulate in the bones, teeth, and blood. Although each individual has a different level of sensitivity, small children and fetuses are most sensitive to adverse heath effects from lead. Lead can cause kidney damage, anemia, and cognitive damage in young children and can slow educational development. Fetal exposure to lead through the mother can result in impaired neurological development, premature birth, and lowered birthweight. Adult males with elevated lead levels can experience high blood pressure, and, in some cases, infertility (Hudson and Gileras 1976).

Lead Regulations

Through the passage of the Safe Drinking Water Act (SDWA), PL93-523, in 1974, the U.S. Congress authorized the USEPA to develop national regulations to control contaminants in drinking water "which may have any adverse effect on health" or the overall aesthetics of drinking water. In 1986, the act was amended. Future regulations resulting from passage of these amendments will propel the water supply industry in the United States into a new era of regulations, monitoring, and compliance requirements. Since the SDWA amendments, a number of regulations have been proposed or finalized. The 1986 SDWA amendments set schedules for regulating 83 compounds by June 1989; an additional 25 compounds will be added to the list of regulated compounds over the 3 years. The amendments also specified a ban on the use of lead materials for public water systems. Lead materials are defined as: (1) pipe and pipe fittings with more than 8 percent lead, and (2) solder or flux containing more than 0.2 percent lead (Hem and Durum 1973). The 1986 SDWA was amended again in 1988 by the Lead Contamination and Control Act (PL100-572). This act focused on leadlined water coolers, lead in school drinking water, and lead poisoning prevention.

Lead and Copper Rule

The Lead and Copper Rule, promulgated in the June 7, 1991 *Code of Federal Regulations* (40 CFR 141.80-91), addresses both lead and copper levels in source waters and entry of lead and copper into the

water from corrosion of distribution piping and household plumbing. The rule requires public water systems to undertake the following actions:

- evaluate lead and copper levels at consumer taps,
- conduct a materials survey to target corrosion sampling sites, and
- conduct a sampling program to determine compliance.

Depending on results of the sampling program, the rule may require the following actions:

- prepare a treatment plan for approval by the primacy agency,
- optimize treatment, and
- initiate a public education program.

The rule affects two classifications of public water systems:

- community water systems: public water systems with at least 15 service connections used all year or 25 year-round residents
- non-community, nontransient water systems: public water systems that serve at least 25 people over 6 months a year.

The community water system classification was further subdivided based on the system size (number of customers) into:

- small, fewer than 3300 people,
- medium, 3300 to 50,000 people, and
- large, more than 50,000 people.

Contaminant Level in Product Water

The Lead and Copper Rule establishes action levels for lead and copper in product waters, i.e., water following treatment by a water treatment plant which is then sent through the distribution system. The current action levels are 15 µg/L for lead and 1300 µg/L for copper obtained from samples at the tap. The USEPA has identified several treatment technologies for removing lead and copper in the treatment plant before entry to the distribution system and controlling lead contamination within distribution systems. The USEPA had provided a summary of corrosion control treatments (USEPA 1992). They are:

- coagulation/filtration,
- ion exchange,
- pH and alkalinity control,
- corrosion inhibitors,
- lime softening, and
- reverse osmosis.

Contaminant Level at the Tap

Under the regulation, utilities will have to sample tap water that has been standing in the interior plumbing over 6 hours. This monitoring will evaluate the amount of lead and copper in the water due to corrosion. Samples must be taken from homes with the highest potential risk (those with lead service

11

lines or copper plumbing). The monitoring will be used to determine the need for corrosion control treatment and/or a public education program. The action levels are as follows:

- maximum lead levels greater than 15 µg/L in more than 10 percent of samples from monitoring high risk homes, and
- more than 10 percent of samples contain more than 1300 µg/L (1.3 ppm) copper.

Measurements exceeding any of these action levels would "trigger" the installation or utility to submit a treatment plan to the state.

Treatment Plan

If action levels are exceeded, the installation or utility must submit a water treatment plan to the state after monitoring. The treatment plan must include:

- pipe loop or laboratory studies,
- analyses of data gathered from these studies to estimate treatment and operational requirements to minimize corrosion,
- water system treatment, and
- monitoring to evaluate treatment effectiveness.

If the initial monitoring reveals lead levels greater than 15 µg/L in more than 10 percent of targeted samples, a public education program would be required.

Water Quality Monitoring Requirements

The installation or utility must undertake source water monitoring and tap water monitoring if the tap water action level is exceeded.

Source Water Monitoring. Utilities will have to demonstrate that the water entering distribution systems after treatment does not exceed 15 µg/L and 1300 µg/L for lead and copper, respectively. Samples must be taken at the entry points to the distribution system. Historical data may be used to prove compliance if the samples were taken at the right frequency from the proper locations. Table 1 shows the sampling frequency based on population served and type of source water.

Tap Water Monitoring. Before beginning a monitoring program to evaluate corrosion, the utility must complete a materials survey to identify "targeted" residences, or those with the highest potential risk. Important materials to be located and identified include lead service lines, lead goosenecks/pigtails, lead solder, copper tubing, and faucets containing lead. Residences selected for monitoring must be located at the end of the distribution system and fulfill one of the following requirements:

- contain copper pipes with lead solder installed after 1982, or
- have lead service lines or lead interior pipes.

There is a tiered approach to selecting buildings to use for evaluating risk. The utility must identify 50 percent more sampling sites than what would actually be needed for compliance because it is likely that some samples will not meet testing requirements (e.g., insufficient standing time).

Table 1

Sampling Frequency for Determining Compliance With the Lead Regulations

Population Served	Water Source	Required Sampling Frequency
<500	ground	annually
<500	surface	annually
500 to 3300	ground	annually
500 to 3300	surface	quarterly
>3300	ground	annually
>3300	surface	quarterly

Public Education

All public water systems must initiate a public notification and education program if they fail to meet the action levels. This program would be part of their submitted treatment plan. For community water systems, this would involve providing information on sources of lead in drinking water and other sources of lead in the environment, potential health risks associated with lead, and actions consumers can take to reduce exposure to lead in drinking water. The USEPA has developed camera-ready print materials and model public service announcements that must be included by the utility in all materials either printed or distributed through the electronic media within 60 days of failing to meet the lead action levels. The utility must follow up with semiannual reminders. The utility must also offer to sample any customer's water and provide the results of the analysis. Nontransient, noncommunity water systems must post the public notification and educational information in a public place, hold at least one public meeting, and distribute pamphlets on lead in drinking water quarterly.

Sources of Lead and Species Formation

The potential for lead exposure from water sources (either ground or surface water) is limited. Water sources, water treatment chemicals, and transmission and distribution systems usually do not add significantly to lead levels in drinking water. The primary source of lead in drinking water comes from the contact between lead-containing plumbing materials and corrosive water. Lead service piping, solders containing high levels of lead, and household plumbing fixtures are the most likely contributors to high lead levels at the tap (Temkar et al. 1991).

Mobilization of lead from plumbing and service lines is the major mechanism for entrance of lead into drinking water (AWWARF 1990). The chemical equilibria are complex and many factors influence this mobilization, including a water's corrosive tendencies. Corrosion of lead-containing materials occurs when an oxidizing agent, such as dissolved oxygen or various chlorine species, causes metallic lead to be converted to an oxidized form, usually Pb^{2+}, which can then be taken up by water. Corrosion is an electrochemical reaction requiring an anode, cathode, and an electrolyte (water) for the reaction to proceed. The concentrations of lead present in drinking water result from this corrosion (oxidation) reaction and the solution chemistry of the oxidized lead species.

This oxidation and mobilization of lead are governed by the level of oxidant in the water, the pH level, and the complexation of Pb^{2+} by various ions or molecules in the water (ligands), such as hydroxide,

carbonate, ammonia, orthophosphates, and polyphosphates. Lead corrosion can be restricted by the formation of relatively insoluble films on the surface of the lead-bearing material. These films, called passivating films, can bar movement of metallic lead into solution or movement of the oxidizing agent to the pipe or appurtenance surface. Some important passivating deposits that have been identified include $Pb_3(CO_3)_2(OH)_2$ (hydrocerussite), $Pb_{10}(CO_3)_6(OH_6)O$ (plumbonacrite), $PbCO_3$ (cerussite), and PbO_2(plattnerite, a Pb^{4+} oxide). The forms of lead orthophosphate solids, some of which may be less soluble than hydrocerussite, have not been well defined; two possibilities, however, are $Pb_5(PO_6)_3OH$ (hydroxypyromorphite) and $Pb_3(PO_4)_2$ (tertiary lead orthophosphate).

Most of the understanding of the chemistry of lead corrosion and the formation and behavior of lead complexes has been accomplished using chemical solubility models. Simple systems can be simulated and controlling solids identified and evaluated theoretically. Much work remains to understand "real world" behavior of lead and complexes in drinking water, although current knowledge allows sufficient understanding to estimate water quality changes needed to reduce lead levels at the tap. The most important factors affecting lead mobilization are the physical and chemical characteristics of the potable water in contact with the lead-bearing materials. The parameters usually considered most important are: pH, oxidant concentrations (e.g., dissolved oxygen, chlorine, chloramines), dissolved inorganic carbon (DIC), alkalinity, temperature, and corrosion inhibitor concentrations. DIC is a parameter not commonly used by water supply professionals, but its impact on lead mobilization has been well documented. DIC is related to alkalinity and pH. Further discussion of these characteristics, relationship to lead-containing materials, and treatment and control approaches for lead in specific situations is presented by the AWWARF (1990).

Lead forms several species in the presence of water. Researchers (Hem and Durum 1973) reported that the least soluble common forms of lead in oxidizing systems are lead carbonate [$PbCO_3$], lead hydroxide [$Pb(OH)_2$], and lead hydroxycarbonate [$Pb_3(OH)_2(CO_3)_2$]. At 25 °C, lead hydroxide is the most stable solid form (Hem and Durum 1973).

Water System Piping Material

Home plumbing lines are usually constructed from different materials than transmission or distribution mains and construction materials will vary based on the date the lines were put in service, application, and cost of materials. Often local building codes dictate the use of certain pipe materials.

Older water systems are more likely to contain cast iron, lead, and vitrified clay pipe distribution lines. The introduction of newer pipe materials, however, has significantly changed pipe-use trends. For example, ductile iron pipe, introduced in 1948, has completely replaced cast iron pipe. Currently, all ductile iron pipe is lined with cement or another material (unless specified otherwise). The percentage of asbestos-concrete (A-C) pipe use increased from less than 6 percent to more than 13 percent between 1960 and 1975. The use of plastic pipe is also increasing, due partly to improvements in the manufacture of larger-sized pipe and partly to greater acceptance of plastic pipe in building codes (Gross 1977).

Many older systems still have lead service lines in operation. Before 1960, copper and galvanized iron were the primary service line pipe materials. Although copper and galvanized iron service line pipes are commonly used, recent trends show an increased use of plastic pipe.

New homes that were plumbed with copper pipe and 50:50 lead/tin solder or older homes plumbed with lead pipe are most likely to expose residents to a high lead concentration in drinking water. Scientific data indicate that new homes pose a greater risk of lead contamination. Lead levels decrease over time as a coating builds up inside the plumbing. It can take from 3 months to 5 years to develop

14

a calcium carbonate coating on the piping. Until that coating is in place, lead from the pipe or solder is more likely to leach into the water in the plumbing system (Gross 1977).

Langelier's Saturation Index

The fundamental reaction in the Langelier Index is:

$$CaCO_3(s) + H^+ = Ca^{2+} + HCO_3^-$$ [Eq 1]
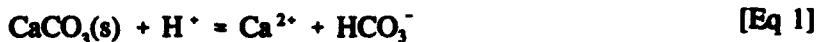
When equilibrium is reached:

$$K = \frac{[Ca^{2+}][HCO_3^-]}{[H^+]}$$ [Eq 2]

Rearranging and taking the logarithm:

$$pH_s = pCa^{2+} + pHCO_3^- - pK$$ [Eq 3]

where,
- pH_s = equilibrium (saturation) pH value for the fundamental Langelier equation
- pCa^{2+} = equilibrium calcium content
- $pHCO_3-$ = total alkalinity where the pH value is less than 9.5
- pK = arithmetic difference between the second protolysis constant for H_2CO_3 and the solubility product constant for calcium carbonate ($CaCO_3$).

Thus, the pH is a calculated value from the three terms on the right-hand side of the equilibrium equation. The saturation index is calculated from:

$$SI = pH_{ac} - pH_s$$ [Eq 4]

where,
- pH_{ac} = actual pH value of the water.

When pH_{ac} is less than pH_s, negative SI values are obtained and the water tends to be corrosive. When the pH_{ac} is greater than the pH_s, positive SI values are obtained and the water tends to form scale (Montgomery 1985).

Water Quality Effects on Corrosion Rates

Strict limitations are required in a treatment schedule to actually eliminate corrosive tendencies not only for economic reasons, but also because there is a limited number of parameters that can be effectively controlled. In many cases the offending parameter will be at milligram or microgram levels, and it is the removal of the last vestige that is expensive. The characteristics of drinking water that affect the occurrence and rate of corrosion can be classified as (1) physical, (2) chemical, and (3) biological. In

15

most cases, corrosion is caused or increased by a complex interaction among several factors (discussed below). Controlling corrosion may require changing more than one of these factors because of their interrelationship (Rossi 1980).

Physical Characteristics

The different types of physical characteristics that affect the corrosivity of the water are discussed in this section.

Velocity. Flow velocity has seemingly contradictory effects. In waters with scale-forming tendencies, high flow velocities can aid in the formation of protective coatings by transporting the protective material to the surfaces at a higher rate. However, high flow velocities are usually associated with erosion in copper pipes in which the protective wall coating or the pipe material itself is removed mechanically. High velocity waters combined with other corrosive characteristics can rapidly deteriorate pipe materials.

Another way in which high velocity flow can contribute to corrosion is by increasing the rate at which dissolved oxygen (DO) comes in contact with pipe surfaces. Oxygen often plays an important role in determining corrosion rates because it enters into many of the chemical reactions that occur during the corrosion process.

Extremely low velocity flows may also cause corrosion in water systems. Stagnant flows in water mains and household plumbing have occasionally been shown to promote tuberculation and pitting, especially in iron pipe. Low flows have also been shown to cause or contribute to corrosive biological growths.

Temperature. The effects of temperature are complex and depend on the water chemistry and type of material in the system. Generally, the rate of all chemical reactions, including corrosion reactions, increases with increased temperature. All other aspects being equal, hot water should be more corrosive than cold. Water that shows no corrosive characteristics in the distribution system can cause severe damage to copper or galvanized iron hot water heaters at elevated temperatures (Kennett 1984). Temperature significantly affects the dissolution of $CaCO_3$. Less $CaCO_3$ dissolves at higher temperatures, which means that $CaCO_3$ tends to come out of solution (precipitate) and form a protective scale more readily at higher temperatures. The protective coating resulting from this precipitation can reduce corrosion in a system. On the other hand, excessive deposition of $CaCO_3$ can clog hot water lines (Lane 1982). A temperature increase can change the entire nature of the corrosion. For example, a water that exhibits pitting at cold temperatures may cause uniform corrosion when hot. Although the total quantity of metal dissolved may increase, the attack is less acute, and the pipe will have a longer life.

Chemical Characteristics

The chemical characteristics of water have the most profound effects on the corrosive qualities of the water. The chemical components that are of greatest importance are pH, alkalinity, DO, chlorine residual, total dissolved solids (TDS), hardness, chloride, sulfate, and hydrogen sulfide.

pH. pH is a measure of the concentration of hydrogen ions (H^+) in water. Since H^+ is one of the major substances that accepts the electrons given up by a metal when corroded, pH is an important factor to measure. At pH values below about 5, both iron and copper corrode rapidly and uniformly. At values higher than 9, both iron and copper are usually protected. However, under certain conditions corrosion may be greater at high pH values. Between pH 5 and 9, pitting is likely to occur if no protective film is present. The pH also affects the formation or solubility of protective films (Singley 1978).

16

Alkalinity. Alkalinity is a measure of a water's ability to neutralize acids. In potable waters, carbonate, CO_3^{2-}, and bicarbonate, HCO_3^-, are the compounds most often responsible for alkalinity. The bicarbonate portion of alkalinity can neutralize bases. This property is termed "buffering." A measure of buffering is the "buffer capacity." Carbonate does not provide any buffer capacity for bases because it has no H^+ to react with the base. Buffer capacity can best be understood as resistance to change in pH (Rossi 1980).

Bicarbonate and carbonate affect many important reactions in corrosion chemistry, including the tendency of water to lay down a protective metallic carbonate coating on pipes. These compounds also affect the concentration of calcium dissolved from cement-lined pipe or from A-C pipe. Alkalinity also reduces the dissolution of lead from lead pipes or lead-based solder by forming a protective coating of lead carbonate on the metallic surface (Montgomery 1985).

Dissolved Oxygen. According to many corrosion experts, oxygen is the most common and the most important corrosive agent (Rossum 1987). In many cases, it is the substance that accepts the electrons given up by the corroding metal according to the following equation that allows the corrosion reactions to continue.

$$O_2 \ + \ 2H_2O \ + \ 4e\text{-} \ \rightleftharpoons \ 4OH^- \qquad \text{[Eq 5]}$$
(free oxygen + water + electrons $\rightleftharpoons$ hydroxide ions)

Oxygen also reacts with hydrogen gas, H_2, and oxygen is released at the cathode. This reaction removes hydrogen gas from the cathode and allows the corrosion reactions to continue. The equation is:

$$2H_2 \ + \ O_2 \ \rightleftharpoons \ 2H_2O \qquad \text{[Eq 6]}$$
hydrogen + oxygen $\rightleftharpoons$ water

Hydrogen gas (H_2) usually covers the cathode and retards further reaction. This is called polarization of the cathode. The removal of the H_2 by the above reaction is called depolarization.

Chlorine Residual. Chlorine lowers the pH of the water by reacting with the water to form hydrochloric acid and hypochlorous acid. This reaction makes the water potentially more corrosive. In waters with low alkalinity, the effect of chlorine on pH is greater because such waters have a lower capacity to resist pH changes (buffer capacity). Tests show that the corrosion rate of steel is increased by free chlorine concentrations greater than 0.4 mg/L. Chlorine can be a stronger oxidizing agent than oxygen in neutral (pH 7.0) waters (Larson 1975).

Total Dissolved Solids (TDS). Higher TDS indicates a high ion concentration in the water, which increases conductivity. Increased conductivity in turn increases the water's ability to complete the electrochemical circuit and to conduct a corrosive current (Lane 1982). The dissolved solids may affect the formation of protective films by forming various complexes with the potential film-forming agent.

Hardness. Hardness is caused predominately by the presence of calcium and magnesium ions and is expressed as the equivalent quantity of $CaCO_3$. Hard waters are generally less corrosive than soft waters if sufficient calcium ions and alkalinity are present to form a protective lining ($CaCO_3$) on the pipe walls (Singley 1978).

Chloride and Sulfate. Chloride (Cl^{-1}) and sulfate (SO_4^{2-}) may cause pitting of metallic pipe by reacting with the metals in solution and causing them to stay soluble, thus preventing the formation of protective metallic oxide films (Singley 1978). Chloride is about three times as active as sulfate in

17

preventing films from forming. The ratio of the chloride plus the sulfate to the bicarbonate [(Cl $+SO_4^{2-}$)/ HCO_3^-] has been used by some corrosion experts to estimate the corrosivity of a water.

Hydrogen Sulfide. Hydrogen sulfide (H_2S) accelerates corrosion by reacting with the metallic ions to form insoluble sulfides. It attacks iron, steel, copper, and galvanized piping to form "black water," even in the absence of oxygen (Shoeyink and Jenkins 1980). An H_2S attack is often complex, and its effects may either begin immediately or may not become apparent for months.

Biological Characteristics

Both aerobic and anaerobic bacteria can induce corrosion. Two common "corrosive" bacteria in water supply systems are iron-oxidizing and sulfate-reducing bacteria (Sum X Corporation 1982). Each can aid in the formation of tubercles in water pipes by releasing by-products that adhere to the pipe walls. In studies performed at the Columbia, MO, water distribution system, both sulfate-reducing and sulfur-oxidizing organisms were found where "red water" (rust) problems were common.

Many organisms form precipitates with iron. Their activity can result in higher iron concentrations at certain points in the distribution system due to precipitation, as well as bioflocculation of the organisms. Controlling these organisms can be difficult because many of the anaerobic bacteria exist under tubercles, where neither chlorine nor oxygen can get to them. In addition, these organisms normally occur in dead end or low-flow areas where a chlorine residual is not present or cannot be maintained.

Corrosion Inhibitors

Corrosion can be controlled by adding chemicals that will form a protective film on the surface of the pipe and provide a barrier between the water and the pipe. These chemical inhibitors reduce corrosion but do not completely prevent it (Boffardi and Schweltzer 1984).

The three types of chemical inhibitors commonly approved for use in potable water systems are chemicals that cause $CaCO_3$ scale formation, inorganic phosphates, and sodium silicate. Several hundred commercially available products are listed with various state and Federal agencies for this use.

Scale-forming Chemicals

If the chemicals are being fed into the system automatically, interruptions in the chemical feed can cause loss of the protective film by allowing it to redissolve. Low chemical concentrations may prevent the formation of a protective film. Both interrupted feed and low concentration can result in pitting. On the other hand, excessive use of some alkaline inhibitors over a long time can cause an undesirable buildup of scale, particularly in harder waters. The key to good corrosion inhibitor treatment is to control the chemical feed.

Water flow rates must be sufficient to continuously transport the inhibitor to all parts of the metal surface, otherwise an effective protective film will not be formed and maintained; corrosion will then be free to take place. For example, corrosion inhibitors often cannot reduce corrosion in storage tanks because the water is not flowing, and the inhibitor is not fed continuously. To avoid corrosion in tanks, it is necessary to use a protective coating, cathodic protection, or both. Similarly, corrosion inhibitors are not as effective in protecting dead ends as they are in those sections of mains that have a reasonably continuous flow.

Inorganic Phosphates

Phosphates are used to control corrosion in two ways: to prevent excessive scaling or $CaCO_3$ buildup and to prevent corrosive attack of a metal by forming a protective film on the surface of the pipe wall. Phosphates inhibit the deposition of a $CaCO_3$ scale on the pipe walls, which is an advantage only in the waters in which excessive scaling occurs. The mechanism by which phosphates form a protective film and inhibit corrosive attack, though not completely understood, is known to depend on flow velocity, phosphate concentration, temperature, pH, calcium, and carbonate levels (Boffardi and Schweltzer 1984).

Several different types of phosphates are used for corrosion control, including polyphosphates, orthophosphates, glassy polyphosphates, and bimetallic polyphosphates. Recent developments in corrosion control include the use of zinc with a polyphosphate or orthophosphate.

Low dosages (about 2 to 4 mg/L) of glassy phosphates, such as sodium hexametaphosphate, have long been used to solve "red water" problems. In such cases, adding glassy phosphates masks the color, and the water appears clear because the iron is tied up as a complex ion. The corrosive symptoms are removed, but the corrosion rate is not reduced. Controlling actual metal loss requires glassy phosphate dosages up to 10 times higher (20 to 40 mg/L). Other glassy phosphates that contain calcium as well as sodium are more effective as corrosion inhibitors. Adding zinc with a phosphate has been used successfully to both inhibit corrosion and control "red water" at dosages of about 2 mg/L. The zinc phosphate treatment has also been used to eliminate rusty water, blue-green staining, lead pickup, and to reduce measured corrosion rates of metal.

Sodium Silicate

Sodium silicate (water glass) has been used for over 50 years to reduce corrosivity, although the way in which it forms a protective film is still not completely understood. However, it can effectively reduce corrosion and "red water" complaints in galvanized iron, yellow brass, and copper plumbing systems in both hot and cold water. Adding lime and using silicate treatment for corrosion is most effective for soft waters of low pH and high oxygen content. In older systems that already contain scale, silicate treatment may displace the accumulated scale (Kennett 1984).

Case Studies

Several different case studies have been conducted to determine the sources of corrosion and evaluate available treatment options that may reduce corrosion in distribution systems.

Lead Corrosion From Faucets

The principal sources of lead in drinking water are corrosion by-products of various distribution system components and home plumbing materials, such as lead service lines and lead solder. Several preliminary studies have been conducted on the leaching of trace metals from faucets. Samuels and Meranger (1984) performed experiments by turning water-filled kitchen faucets upside down and holding the water in the faucets with inlet and outlet stoppers for two successive 24-hour periods. Tests were conducted with five different raw and treated waters with pH values ranging from 6.2 to 8.6. In low pH waters, lead was found in concentrations up to 55 mg/L. Some of the faucets had lead-soldered copper joints that contributed to the high lead values.

In a pipe-loop corrosion study performed by the Illinois State Water Survey, chrome-plated sampling taps on the pipe loops were suspected of contributing considerable amounts of lead to the samples drawn

from the loops. To verify that the faucet did contribute lead, a chrome-plated faucet was placed at a "T" connection ahead of the loop. After a 1-day retention time, the faucet had contributed lead to a level of 0.099 mg/L in a 125 mL sample. This level decreased over time. As a result of this finding, a 2-week experiment on the leaching of trace metals from six new sampling taps was performed using an technique similar to that of Samuels and Meranger. The tests were performed using deionized water (three faucets) and Champaign, IL, tap water (three faucets). Samples were collected daily (24-hour retention times) during the 2 weeks and were analyzed for lead, cadmium, zinc, iron, and copper. With deionized water, the first samples from the three faucets had lead concentrations near 100 mg/L, which then tapered off to 1 to 10 mg/L at the end of the 2 weeks. With Champaign tap water, the first samples had 1 mg/L of lead, which tapered off to 0.1 to 0.3 mg/L (Shock and Neff 1988).

Gardels and Sorg (1989) constructed a test system to evaluate lead leaching from 12 different kitchen faucets. A storage tank, pressure pump, and manifold system were operated to simulate, as closely possible, the use of kitchen faucets in a household plumbing system. Leaching of lead from the faucets s determined for retention times ranging from 30 minutes to 34 days using distilled water (a very ...gressive water) and Cincinnati, OH, tap water (a nonaggressive water).

The following conclusions were drawn from the results of this study:

- Depending on the water quality, new cast-brass faucets could contribute lead to drinking water in excess of the new proposed "no action level" of 10 µg/L.

- Sixty to 75 percent of the lead leached from a common kitchen faucet appears in the first 125 mL of water collected from the faucet. After 200 to 250 mL of water has flowed, 95 percent or more of the lead has normally been flushed from the faucets.

- With the USEPA proposed sampling procedure using 1-L samples, nonmetallic faucets or faucets with a small amount of brass should be able to meet the 10 µg/L "no action level," even if the water is very aggressive. A 1-L sample will dilute the lead leached from a faucet to levels normally below 10 µg/L (assuming no lead contribution from other lead sources upstream of the faucet).

Corrosion Rate Model

A study conducted by Pisigan and Singley (1985) tested 15 synthetic waters with saturation indexes ranging from -2.12 to +1.90. In addition, two more water samples were tested to compare their corrosion characteristics with the waters containing calcium, alkalinity, and other ionic solutes (Pisigan and Singley 1985).

The corrosion rate of mild steel coupons immersed in each water was measured after 1, 3, 5, and 10 days by the weight loss method. The corrosion rate in all of the waters tested in jar systems containing 5.0 ± 0.2 mg/L DO exhibited a general decreasing trend with time. Corrosion was very rapid in the first through third day of immersion and then did not change much after the fifth and tenth days. The decreasing trend of corrosion rate could be attributed to two important factors: (1) the formation of corrosion products that adhered to the metal surface and thus decreased the progress of corrosion either by passivating the metal or by providing coating on the metal surface, which then resisted further corrosive attack, and (2) the decrease in the thermodynamic potential of the metal toward further release of metallic ions into the solution after the water had become enriched with those ions during the initial stages of corrosion (Pisigan and Singley 1985).

No simple trend of corrosion rate with LI could be deciphered. Some waters with a negative LI value were more corrosive than waters with a positive LI. However, other waters with a negative LI were less corrosive than some waters with a positive LI. The decrease in the LI did not significantly correlate with an increase in corrosion rate. For instance, water with the LI = -1.06 had a higher average corrosion rate than water with the LI = -2.21 and -1.48. Water with an LI = -0.73 and water with an LI = -0.51 had higher corrosion rates than water with an LI = -0.86. Similar observations were also found for waters with a positive LI. An increase in the positive values of LI did not correspond to decreasing corrosion rates even though it would be expected that the waters with a higher LI would be increasingly protective. Waters with an LI = +1.90 and an LI = +1.43 had higher corrosion rates than a water with an LI = +1.03.

A two-fold increase in corrosion occurred after raising the DO from 1.5 to 5.0 mg/L and a 3.5-fold increase occurred when the DO was increased from 5.0 mg/L to 9.0 mg/L. The acceleration of the corrosion rate with an increase in DO was due to the enhanced reaction rate occurring in both the anode and cathode surfaces of the metal.

Pisigan and Singley (1985) constructed an empirical eight-variable model. Their model indicated that the corrosion rate of mild steel under the experimental conditions was influenced by several factors other than the waters' tendency to precipitate or dissolve calcium carbonate. The corrosion rate was also influenced by dissolved oxygen, chloride, sulfates, calcium, alkalinity, buffer capacity, and immersion time. A four-variable model derived from multivariate regression analysis defined the corrosion rate as a function of only four independent parameters: total dissolved solids, dissolved oxygen, Langelier Index, and exposure time.

PLS Simulation of Lead Dissolution

A study by Temkar, Scholze, and Smith (1990) was conducted using the CERL-PLS to simulate lead dissolution from lead soldered plumbing in the drinking water distribution system at a U.S. Army base. Two separate PLSs were used during the experiments. One system was fitted with a copper loop with 50:50, lead/tin soldered joints. This copper loop was approximately 6 ft long and contained 22 soldered joints. A second loop contained two galvanized iron pipe sections and two copper pipe sections. The galvanized/copper loop contained four lead coupons that provided a total surface area of 13.5 sq in. The soldered loop was unchanged throughout the experiments while the coupons and pipes in the galvanized loop were replaced at the beginning of each experiment.

The four experiments of the study were:

1. Water produced at the plant without further treatment,
2. Product water plus sodium bicarbonate to raise the total alkalinity to 150 mg/L as $CaCO_3$,
3. Product water plus sodium silicate to raise the sodium silicate concentration to 10 mg/L, and
4. Product water plus sodium bicarbonate and sodium silicate to raise the respective concentrations to 150 mg/L and 10 mg/L.

The results of the soldered loop experiments indicated that lead concentrations decreased with each experiment regardless of the type of treatment. It was determined that the primary factor for this result was a decrease in total lead exposed due to lead dissolution since the soldered joints in the copper loop were not replaced (Temkar, Scholze, and Smith 1990).

The researchers concluded that the experimental conditions for the galvanized loop were better controlled compared to the soldered loop and were able to better determine the effectiveness of each treatment. The sodium silicate treatment without increased alkalinity was the most effective treatment among the options studied.

21

The researchers also concluded that it was feasible to approximate lead dissolution in soldered plumbing systems using the CERL-PLS and the effect of various treatment options can be evaluated.

Zinc Orthophosphate

The use of zinc orthophosphate (ZOP) for corrosion control has been widely reported. The information and data generated by several water utilities that are using ZOP are presented in the following paragraphs.

Portsmouth, VA

The metallic ion concentration of Portsmouth, VA tap water was monitored for several periods between October 1973 and January 1976 (Feigenbaum, Galor, and Yohalom 1978). During this sampling period, water temperatures averaged 60 °F and had an average pH of 7.39. The iron (Fe) content in the system, 22 miles from the plant, ranged from 0.01 to 2.70 parts per million (ppm) with an average of 0.45 ppm for 29 samples. Corresponding samples from the plant effluent averaged 0.04 ppm Fe with a range from 0.01 to 0.05 ppm. This represented a substantial iron pickup from the cast iron distribution system. Treatment for corrosion control up to this time had consisted of lime and sodium hexametaphosphate. Typical finished water analyses were: total alkalinity, 86 ppm; total hardness, 36 ppm (as $CaCO_3$); calcium hardness, 31 (as $CaCO_3$); pH 7.0; chloride (as Cl^-), 16 ppm; and sulfate (as SO_4^{2-}), 17 ppm.

Zinc orthophosphate was introduced as a corrosion inhibitor in August 1974. In addition to distribution system evaluation using mild steel coupons, two sampling studies were done. The first sampling study was conducted from February through March 1976. The average water temperature was 62 °F and the average pH was 7.14. Samples from 9 locations were taken 12 times. Iron content from these samples averaged 0.03 ppm with a range from 0.02 to 0.12 ppm. The plant effluent samples taken at the same time averaged 0.02 ppm Fe. Another sampling period during July and August 1976 was used to evaluate metal ion pickup during the time when water temperature peaked. The same nine stations were sampled and averaged 0.06 ppm Fe. The plant effluent also averaged 0.06 ppm during the test period.

Mild steel coupons inserted into the distribution system showed reductions in corrosivity from 50.1 percent to 91.0 percent over those in untreated plant water. Corrosion rates varied inversely with the size of mains. The reduction in soluble iron from an average of 0.45 ppm Fe to an average of 0.04 ppm during the study periods reflects a 91.1 percent reduction in iron pickup due to the addition of ZOP.

Pinellas County, FL

Reports of leaking copper plumbing in 1974 resulted in an investigation by the Pinellas County water department to determine the extent and cause of copper corrosion (Boffardi and Schweltzer 1984). A pitting problem and an average copper level of 1.5 ppm were found. Isolated standing water samples contained as much as 5.0 ppm copper. A 65-day bench test gave a 51 percent reduction in the rates of copper corrosion on coupons. Treatment consisted of zinc phosphate inhibitor at 0.3 ppm zinc level after an initial 3-day dosage of 3 ppm zinc.

Copper (Cu) coils connected to timers simulated the 24-hour running-standing cycle of a home system. Standing water samples of treated water averaged 0.5 ppm Cu while the untreated coil averaged 1.51 ppm Cu. Treatment at 0.75 ppm zinc produced a reduction in copper concentrations from 1.5 ppm Cu to 0.65 ppm Cu in standing home water. Two years of operation show occasional fluctuations of copper concentrations that have been linked to problems with the inhibitor feed pump. A feed concentration of 0.5 to 1.0 ppm as zinc was being used to maintain pickup below 1.0 ppm Cu. A week-

long break in inhibitor feed resulted in elevated copper concentrations that required several weeks to stabilize to previous levels.

New London, CT

The New London Water Department participated in a study of metallic ion pickup in home services during September, 1975. The analyses were performed by the U.S. Environmental Protection Agency, Cincinnati, OH ("Current Corrosion Experiences in Large Utilities: Results of a Committee Survey" 1978). The zinc orthophosphate inhibitor had been in use for 6 months before sampling. A typical finished water analysis shows a soft surface water with low hardness and dissolved solids; pH 6.4 to 7.1; M.O. alkalinity 12 ppm; hardness (as $CaCO_3$) 16 ppm; TDS 35 ppm; calcium 12 ppm; chloride (as Cl⁻) 9 ppm.

The sampling procedure in this case called for three samples: an overnight standing sample, a service line sample taken when a temperature drop was noticed, and a main sample after running the tap 5 minutes. All lead concentrations were below the .050 mg/L limit for drinking water. Only one site showed lead above the detection limit of 0.005 mg/L. The average iron concentrations were the same in all three samples and no significant change occurred from the plant effluent. The average copper concentration of all samples collected from copper services was 0.170 mg/L.

3 EXPERIMENTAL PROCEDURE AND EQUIPMENT SETUP

The CERL-PLS was designed to (1) monitor and control the characteristics of water, (2) minimize the effects of all but one type of corrosion at a time, (3) use test specimens that simulate various piping materials used in the distribution system, and (4) closely simulate actual distribution system conditions. Figure 1 is a schematic of the current CERL-PLS design.

Features of the CERL-PLS

The test loop is constructed of 3/4-in. (nominal) polyvinyl chloride (PVC) and chlorinated polyvinyl chloride (CPVC) pipe and fittings. These materials are readily available and have suitable characteristics. This design eliminates all metallic components, except for the corrosion specimens and a flow meter constructed of copper. The test loop is oriented vertically to minimize the amount of suspended matter deposited on the exposed surfaces of the corrosion specimens. A flow controller, a flow rate meter, and regulating valve are provided to maintain flow through the loop at desired rates. If fluctuating water pressure occurs, a pressure regulating valve can be used at the inlet piping of the test loop. A totalizing water meter is also included in the design to verify water use information during monitoring intervals. Chemicals are mixed with water in a 50-gal drum and injected by pump to study the effectiveness of a selected corrosion inhibitor. A sampling valve is installed in the loop to collect water samples periodically for chemical analyses and to verify inhibitor concentrations.

The corrosion tester, shown in Figure 2, was originally developed for use in placing pipe specimens in a service line. It has been adapted into the CERL-PLS design. The design allows easy interchange of pipe specimens of uniform dimensions.

Experimental Use of the CERL-PLS

Two separate systems were used during all phases of the experiments. The first system will be identified as the lead/tin solder loop, which contained two copper pipe specimens that were internally coated with 50:50, lead/tin solder. The second system will be identified as the lead coupon loop, which contained four pure lead coupon specimens. For the first phase of experiments, the two systems were connected in series using nonmetallic flexible hoses. The water that entered the lead/tin solder loop and then passed through the lead coupon loop was supplied either from two 50-gal plastic mixing tanks connected to an electrical pump, or by direct connection to a mainline distribution tap.

For the second phase of experiments, the two loops were connected to separate water sources. For the first experiment of phase two, the lead/tin loop was connected to the 50-gal tanks and the lead coupon loop was connected directly to a mainline tap. For the second experiment of phase two, the connections were reversed.

Sample Size and Sampling Procedure

A 1-L sample was collected from each loop for analysis; 1 L is the standard sampling volume set by the USEPA. Using this volume allows direct comparison with other data without manipulation of the results.

MATERIAL LISTING
MIXER - STATIC
V₃ - MAIN WATER SUPPLY SHUT-OFF VALVE
PRV - PRESSURE REGULATING VALVE
V₁ - TEST LOOP ISOLATION VALVES
FC - FLOW RATE CONTROLLER, PVC, 3GPM
FR - ROTAMETER, 0-5 GPM
M - WATER METER, TOTALIZING
C - CORROSION CUPONS
CERL - PIPE SPECIMENS
V₂ - SAMPLE VALVE, 1/4"
PIPE & FITTINGS - 3/4", SCH. 40, PVC
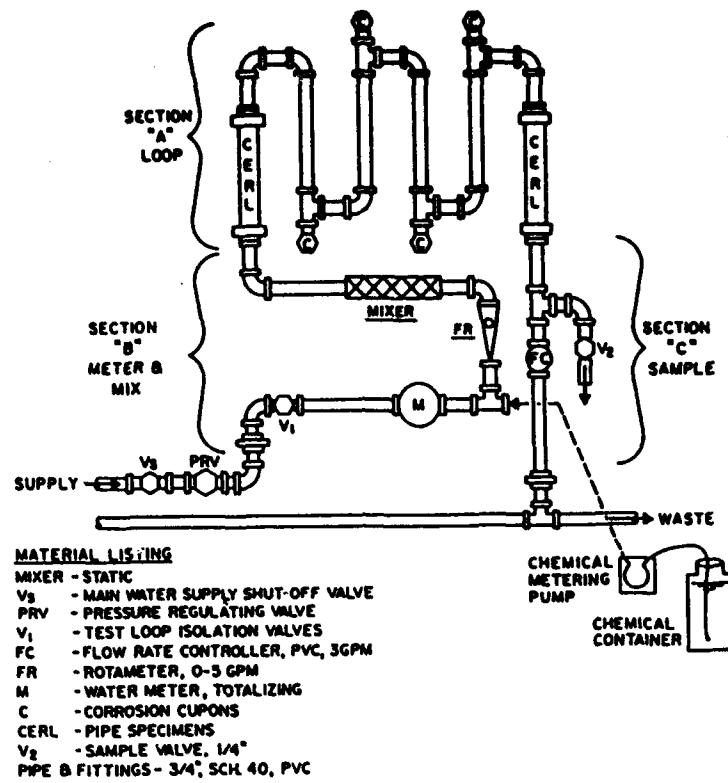
Figure 1. USACERL Pipe Loop System Design.

① 3/4" PVC SERVICE LINE

② I" UNION, PVC, SOCKET TYPE

③ I x 10" PIPE NIPPLE, PVC, SCH. 40

④ I x 3/4" REDUCING BUSHING, PVC, SOCKET

⑤ 3/4" PVC SPACER, SCH. 40, O.D. REDUCED 0.015"

⑥ UNION GASKET

⑦ CORROSION SPECIMENS, 3/4", O.D. REDUCED 0.030", MACHINED FROM SCH. 40 GALVANIZED STEEL OR STEEL PIPE

⑧ 3/4 x ≈2" SPECIMEN SEPARATOR, PVC, SCH. 40, O.D. REDUCED 0.015"
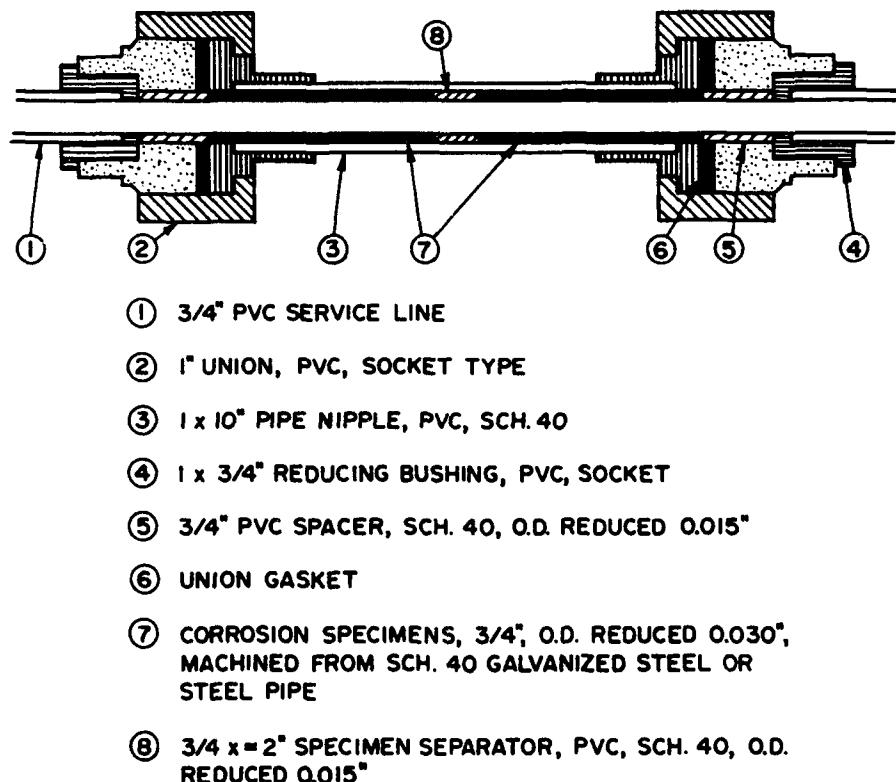
Figure 2. Cross-Section of USACERL Corrosion Tester.

The samples were collected from the sampling valves on the PLS. The sample from the lead/tin loop was collected first by creating pressure inside the PLS by turning on the pump or opening the tap valve, depending on the water being tested, and then opening the sampling valve. After the 1-L sample was collected, the valves that isolate the two loops were opened, pressurizing the lead coupon loop. The 1-L sample from the lead coupon loop was then taken from the sampling valve.

Flow Cycle and Stagnation Period

During phase one, the project was operated using a 24-hour cycle period conducted continuously for 5 days. During phase two, the 24-hour cycle period was continued until the lead concentration reached a consistent value. Each cycle consisted of a sample draw followed by a 1-hour flush, a 6-hour stagnation period, a second sample draw and 1-hour flush, and a 16-hour stagnation period. During the flush periods, the water flowed through both loops at a rate of 2-gallons per minute (gpm) to simulate actual flow velocities in household plumbing systems. The experimental cycle consisted of a sample collection at 8:00 a.m. immediately followed by flushing the system until 9:00 a.m. when all valves were closed to isolate the loops and start the 6-hour retention period. The cycle was continued by collecting the 6-hour samples at 3:00 p.m. immediately followed by flushing the system until 4:00 p.m. when the valves were closed until 8:00 a.m. the next day when the cycle was repeated. The stagnation periods of 6 and 16 hours were chosen because they simulate the average daily and nightly stagnation times that occur in most households.

Corrosion Specimens

The CERL-PLS is capable of exposing a variety of different specimens to the water being tested. The specimens used during the experiments were copper pipes coated with 50:50, lead/tin solder for the lead/tin loop and pure lead coupons in the lead coupon loop. All specimens were mounted to avoid deposition of any material and were electrically isolated.

The lead/tin solder coated pipe specimens (inserts) were 4 in. long with an inside diameter of 3/4 in. Each pipe specimen exposed 9.4 sq in. of pipe wall area to the water. The pipe material was a copper pipe internally coated with 50:50 lead/tin solder and externally coated with a corrosion resistant material so that no copper was exposed.

The coupons used were certified by the Illinois State Water Survey to be pure lead. Each coupon was 1/2 in. wide, 3 in. long, and 1/16-in. thick, with a surface area of approximately 3.4 sq in. The combined total exposure area of the four coupons was approximately 13.7 sq in. The coupons were vertically mounted and electrically isolated with a PVC pipe plug having a nylon or teflon stem. This device placed the coupon in the middle of the pipe so the water contacted all sides.

Both the pipe specimens and coupons were removed, examined, and cleaned both mechanically and chemically at the end of each cycle to remove any corrosion or inhibitor films that may have formed. Mechanical cleaning consisted of sanding with a fine grit sandpaper until any film had been removed. The specimen was then rinsed with distilled water to remove any loosened particles before it was chemically cleaned. Chemical cleaning consisted of immersing the coupon or pipe in glacial acetic acid for 1 minute, rinsing with distilled water for 30 seconds, immersing it in acetone for 1 minute, and finally rinsing again for 30 seconds with distilled water. The coupon was then dried in a 60 °C furnace for 1 hour and stored in a standard laboratory desiccator.

Corrosion Inhibitors

The corrosion inhibitors tested in the project were three types of ZOP and one type of bimetallic zinc polyphosphate (BMP). All four corrosion inhibitors were provided by the Technical Products Corporation and were certified for use in potable water distribution systems. The properties of the four corrosion inhibitors are presented in Table 2.

ZOP 931 is a dry blend synergistic corrosion inhibiting formulation that forms a highly resistant zinc and phosphate protective film. It is available in 50-lb bags and costs $0.77/lb for orders under 30,000 lb; $0.68/lb for larger orders.

ZOP 932 is a liquid corrosion inhibiting formulation developed specifically for use in potable water systems to control corrosion of distribution lines, water heaters, and other contacted metal surfaces. A highly resistant film containing zinc and phosphate provides the protective mechanism. It is available in 55-gal drums or 40,000-lb tank trucks at a cost of $0.31/lb for orders under 24,000 lb; $0.22/lb for larger orders.

ZOP 939 is a concentrated liquid corrosion inhibitor that forms a zinc and phosphate protective film. It comes in 600-lb drums or 42,000-lb tank trucks. The cost is $0.37/lb for orders under 24,000 lb; $0.28/lb for larger orders.

BMP 937 is a granular zinc-metaphosphate formulation that provides corrosion protection by forming a film on all exposed metal surfaces. Besides being a corrosion inhibitor, BMP 937 also has iron and magnesium sequestering characteristics. BMP 937 is available in 50-lb bags at a cost of $0.76/lb for orders under 30,000 lb; $0.65/lb for larger orders.

Mixing the Chemicals

Each chemical inhibitor was first mixed with 500 ml of tap water for 2 minutes using a stir plate. The inhibitor was then divided into two 250-ml portions. The water supply tap was flushed for 1 minute

Table 2

Chemical Characteristics of the Corrosion Inhibitors Tested

Chemical Characteristics	ZOP 931	ZOP 932	ZOP 939	BMP 937
Color	white	clear	clear	white
Physical nature	granular	liquid	liquid	granular
Odor	none	none	none	none
Density (lb/gal)	na	10.6	11.6	na
Specific gravity (70 °F)	1.39	1.273	1.4	1.34
pH	na	0.8	0.8	na
Zinc content (%)	20	8	8	8.2
Phosphate content (%)	20	8	24	50
Freezing point (°F)	na	16	7.2	na
Freeze thaw recovery (°F)	na	60	60	na

27

to avoid contamination. Two 50-gal plastic drums were filled halfway with tap water. The diluted chemicals were added to the tanks, which were subsequently filled. A small mixer stirred the solution and pumped it from one tank into the next through a nonmetallic flexible hose connected at the bottom of each tank. Both tanks were sealed to minimize any change in water quality, such as pH changes, due to equalization with atmospheric carbon dioxide.

Extended Cycle Study

After all four corrosion inhibitors had been studied, an extended cycle study was initiated to determine how long it would take each inhibitor to reach its maximum protection. Unlike the previous experiments, which were conducted for a predetermined five cycles, the extended cycle study was conducted until the lead concentration of the samples had reached a consistent minimum value. The time needed to reach maximum corrosion inhibition was needed to determine if the time for the experiments in phase one was sufficiently long to accurately evaluate the inhibitors. Also, an extended cycle study was conducted using nontreated tap water to determine if the lead concentration would decrease to an acceptable value without adding any chemical corrosion inhibitor. The extended cycles were conducted using the same retention periods and sampling procedure as the previous experiments.

Water Survey

The CERL-PLS can determine the effectiveness of corrosion inhibitors because it simulates the corrosion procedures that occur in household plumbing systems. To determine if the data generated using the CERL-PLS was valid, a water survey was conducted to allow a comparison between values obtained from the CERL-PLS and actual tap water lead concentrations of household plumbing systems serviced by the Rend Lake water plant in southern Illinois. To minimize any variation in water quality, only households that were serviced directly from a main distribution line were contacted to take part in the survey. Of 50 households contacted to participate in the survey, only 7 water samples were successfully collected.

Since the desired samples had to be "first draw samples" taken in the morning before the water had been used, it was necessary for the residents to take a sample in a provided 1-L sampling bottle. Also, a questionnaire was completed by each resident to help determine the value of the data generated from the samples. Figure 3 shows the questionnaire.

Experimental Analysis

For the research project, the amount of corrosion that had taken place was assumed equivalent to the lead concentration in the sample. The concentration was analyzed using the LeadTrak DR/100 Test Kit manufactured by the Hach Company. The 100-ml sample that was needed for the lead analysis was taken from the 1-L sample that had been obtained from the CERL-PLS or residential sample. A comparison of the LeadTrak DR/100 Test Kit and a graphite furnace atomic absorption method conducted by the Hach Company is shown in Table 3. The results of a similar comparison by an independent and certified laboratory using a graphite furnace atomic absorption method are presented in Table 4. The results indicated that the LeadTrak DR/100 Test Kit method was accurate to within 10 percent of the graphite furnace atomic absorption technique.

The pH of the sample was measured immediately after collection by using a Corning Model 120 digital pH meter. The measurement was taken immediately to minimize the dissolution of dissolved

REND LAKE WATER SURVEY QUESTIONS

How old is your home?

How long have you lived in your current home?

What type of plumbing materials are present in your home?

Material	% of total plumbing
Galvanized steel	_____
Copper	_____
Plastic	_____
other_____	_____
other_____	_____

What type of soldering compound was used (what % of lead)?

What type of faucets are present in your home?

Faucet types	Number in home
stainless steel	_____
brass	_____
plastic	_____
other_____	_____
other_____	_____

What types of repairs/additions have been required and who has completed the work (licensed plummer, handyman, self)? Please list in order of most recent to oldest repair.

Date   Type of Repair   Type of Material Used Repaired By

1.
2.
3.
4.

What type of water quality problems have you personally noticed?

Figure 3. Residential Water Sample Questionnaire.

carbon dioxide, which would change the pH. The pH meter was calibrated with buffer solutions of pH 6.86 and pH 10.4 in accordance with standard methods.

The water quality parameters of the source water, Rend Lake, are indicated in Table 5. The parameters were determined by the certified laboratory technicians employed by the Rend Lake Water Conservation District Laboratory.

Table 3

Comparison of Lead Trak vs. Atomic Absorption (A)

Sample	Lead Concentration by Atomic Absorption (µg/L)	Lead Concentration by Hach LeadTrak kit (µg/L)
1	5	5.1
2	40	52.7
3	<4	0
4	5	4.3
5	<2	1.3
6	<4	0.1
7	10	8.1
8	5	5.8
9	22	24.6
10	<2	0
11	<2	1.3
12	8	8.4
13	<2	0

Note: Data reported by Hach Company.

Table 4

Comparison of Lead Trak vs. Atomic Absorption (B)

Sample	Lead Concentration by Atomic Absorption (µg/L)	Lead Concentration by Hach LeadTrak kit (µg/L)
1	72	72
2	1	2
3	34	36
4	14	14
5	3	1
6	7	8
7	46	55
8	80	90
9	51	60
10	608	610
11	763	680
12	161	170
13	1	0

Note: Graphite furnace analyses performed by Daily Laboratories, Indianapolis IN.

Table 5

Chemical Characteristics of Rend Lake Tap Water

Month	Alk., mg/L as $CaCO_3$	pH	Hardness, mg/L as $CaCO_3$	Temp °F	Langelier Index
Aug	34	9.2	70	79	1.2
Sept	37	9.2	66	76	0.9
Oct	42	9.1	77	74	1.1
Nov	34	9.1	72	71	1.1
Dec	10	9.3	82	69	1.3
Jan	18	9.3	87	70	1.2
Feb	25	9.2	75	68	1.1

4 RESULTS AND DISCUSSION

Phase One: Using the CERL-PLS to Evaluate Inhibitors

The results of the experiments conducted during phase one are presented in the following sections. These experiments were conducted to determine the effectiveness of the chemical corrosion inhibitors.

Rend Lake Tap Water Without Inhibitors

Figures 4 and 5 graphically depict the lead concentration of the 6- and 16-hr retention samples, respectively, generated from both loops. The extremely high initial values indicated the water was very aggressive and rapidly corroded the unprotected test specimens. At the end of the fifth cycle, the lead concentrations in all samples had reached an apparent minimum value. The rate of change in lead concentrations from the fourth to fifth cycle had dramatically decreased in the 16-hr retention samples from both loops. The lead concentrations in the fifth cycle, 6-hour retention samples of both loops actually had a slight increase over their respective fourth cycle values.

The decrease in lead concentration was due to formation of a carbonate scale. The scaling was expected since a positive Langelier Index was maintained throughout the experiment. Although the decrease is significant, the lead concentration in all samples from the fifth cycle was still above the proposed maximum contamination level for lead. Also, the slight increase in lead concentration values detected in the 16-hr retention samples from cycle four to five of both loops indicated that the scale formation could have been unstable and the scale may have been subject to being dislodged.

RENDLAKE WATER
NO TREATMENT ADDED

(y-axis: ppb lead, scale 0 to 160; x-axis: 6 hour cycle number, 1 to 5)

Legend: lead/tin pipe ▨ lead coupons ▨
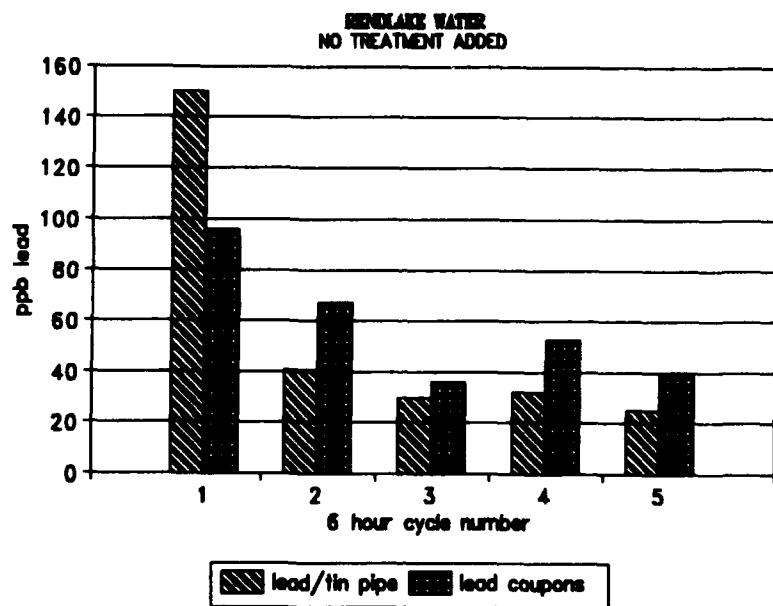
Figure 4. **Lead Concentration of Samples Without Chemical Corrosion Inhibitor and a 6-hr Retention Time.**

RENDLAKE WATER
NO TREATMENT ADDED
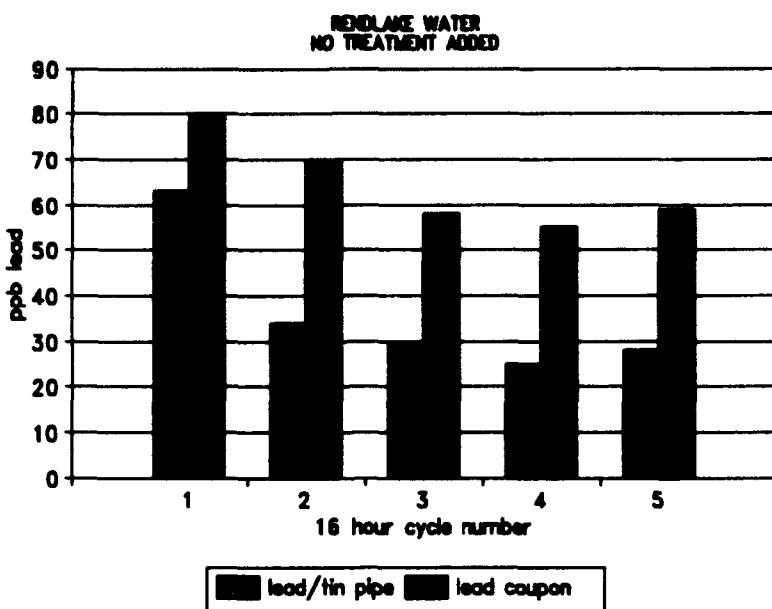
Figure 5. Lead Concentration of Samples Without Chemical Corrosion Inhibitor and a 16-hr Retention Time.

The higher lead values from the lead coupon loop over the lead/tin loop can best be reasoned by the fact that the coupons are pure lead while the pipes in the lead/tin loop are only 50 percent lead. This factor was slightly compensated for since the total exposed area of the pipes was approximately 42 percent greater than the total coupon area.

This experiment indicated that the product water exhibited significant initial corrosion potential. The reduction in the lead concentration, although significant, was not enough to bring the lead concentration below the proposed MCL. Since the experimental apparatus used water from a main distribution line, the water's carbonate concentration would likely be higher than that of the water entering a household plumbing system located on the edge of the distribution service line.

Rend Lake Water With ZOP 932

The second and third experiments performed for the study examined the effectiveness of ZOP 932 at concentrations of 0.5 mg/L and 1.5 mg/L. Cleaned pipes and coupons were installed in the respective loops before the experiment was initiated. The experiment was conducted to determine the ability of ZOP 932 to form a protective film on the exposed metal surfaces.

Figures 6 and 7 show the lead concentrations obtained after adding ZOP 932 at 0.5 mg/L for retention times of 6 hr and 16 hr, respectively. Figures 8 and 9 show the lead concentrations obtained after adding ZOP at 1.5 mg/L for retention times of 6 hr and 16 hr, respectively. It can be seen that ZOP 932 is very effective in lowering the lead concentrations. However, it appears that the increased concentration of ZOP 932 had little effect on the lead concentrations of the samples. The lead values at both concentrations were markedly decreased after just one cycle in both the lead/tin loop and the lead coupon loop for the 6-hr retention time.

The same trend can be seen from a comparison of the 16-hr retention sample's lead concentrations for the dosage rates of 0.5 mg/L (Figure 7) and 1.5 mg/L (Figure 9). The two figures demonstrate again

33
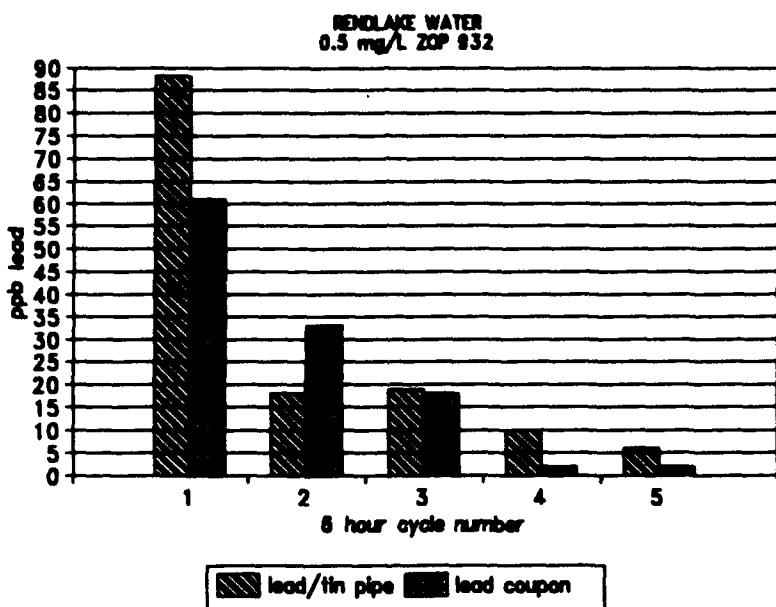
Figure 6. Lead Concentration of Samples With 0.5 mg/L ZOP 932 and a 6-hr Retention Time.
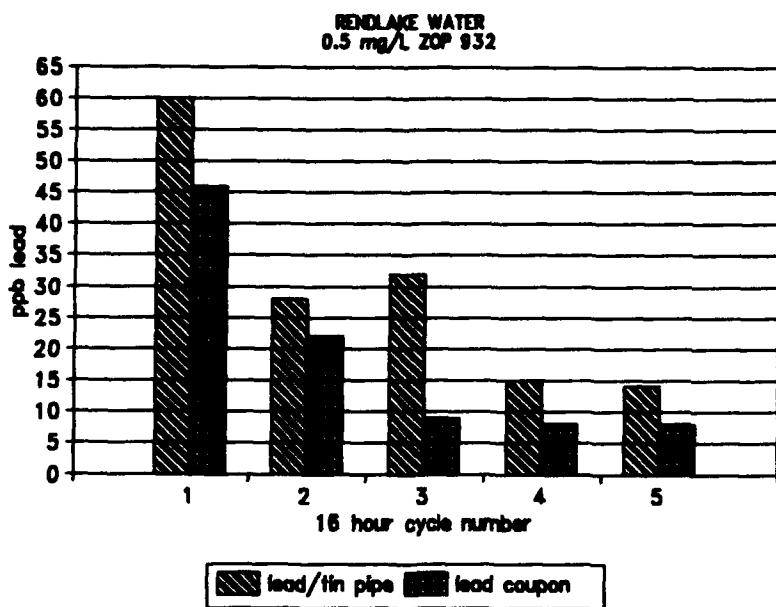
Figure 7. Lead Concentration of Samples With 0.5 mg/L ZOP 932 and a 16-hr Retention Time.
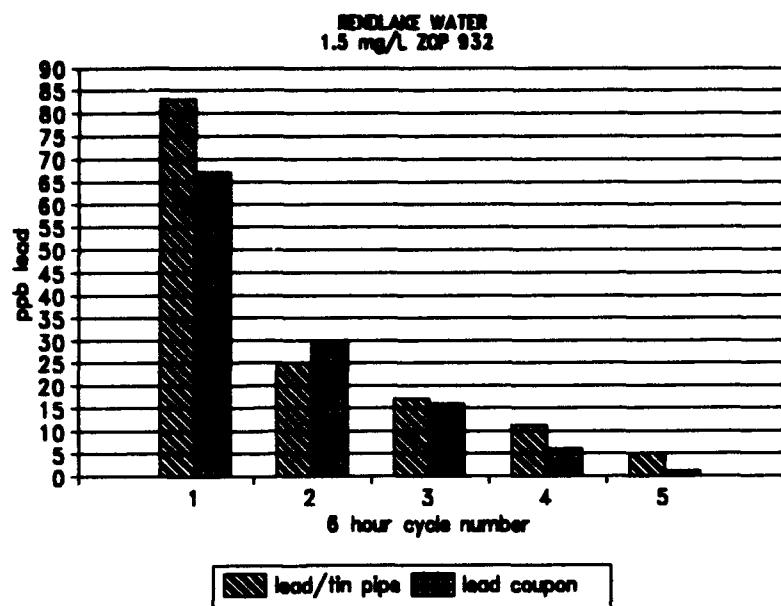
Figure 8.   Lead Concentration of Samples With 1.5 mg/L ZOP 932 and a 6-hr Retention Time.
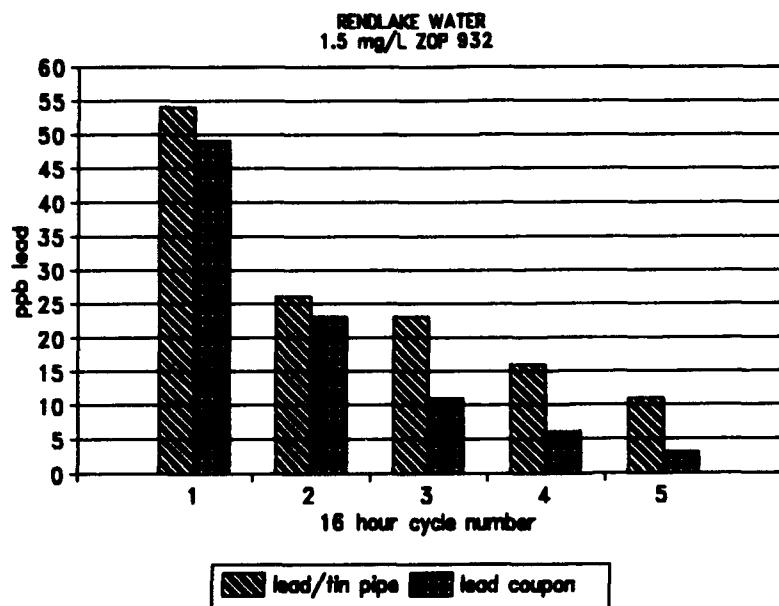
Figure 9. Lead Concentration of Samples With 1.5 mg/L ZOP 932 and a 16-hr Retention Time.

that the sharpest decrease in lead values occurred between the first and second cycles. A significant reduction in lead concentration shows at the end of the fifth cycle.

By comparing the corresponding fifth cycle value of each loop, it is evident that the retention time had a dramatic effect on the lead concentration values, which more than doubled from the 6-hr to the 16-hr retention. The increase with time is expected since corrosion depends on the contact time. However, this was not evident during the previous experiments when no chemical addition was used.

Data from the experiments with ZOP 932 indicate that a protective film rapidly formed on the exposed metal surfaces. The increased concentration from 0.5 mg/L to 1.5 mg/L did not show a dramatic decrease in lead values. The small reduction in the lead concentration indicates that use of the larger dose would not be warranted. The fifth cycle value obtained from both loops at both concentrations and a 6-hr retention time were below the proposed MCL of 10 ppb. The 16-hr retention sample values from the lead/tin loop of 14 ppb and 11 ppb were barely greater than the proposed MCL. Also, the data indicate that the film was not completely formed after the fifth cycle because the lead concentrations had not stabilized. The decreasing values indicate that the lead levels may have reached 10 ppb MCL if the experiment had been continued for another cycle.

Rend Lake Water With ZOP 939

The sixth and seventh experiments used the corrosion inhibitor ZOP 939 at concentrations of 0.5 mg/L and 1.5 mg/L, respectively. Cleaned pipes and coupons were installed in the loops to determine the effectiveness of ZOP 939, which relies on a protective film forming on all exposed metal surfaces for its corrosion inhibition.

Figures 10 and 11 show the lead concentrations obtained after adding ZOP 939 at 0.5 mg/L for retention times of 6 hr and 16 hr, respectively. Figure 10 shows that the most dramatic reduction in lead concentration occurred by the third cycle sampling for both loops. After the third cycle, the change in the corrosion rate continued but was not as significant. Figure 11 shows that the most significant reduction occurred by the second cycle sampling and continued through the end of the fifth cycle. This data indicates that the increased concentration of ZOP 939 increased the rate of the protective film formation.

Figures 12 and 13 show the lead concentrations obtained after adding ZOP 939 at 1.5 mg/L for retention times of 6 hr and 16 hr, respectively. The figures reaffirm the improvement of corrosion protection due to the increased chemical dosage. Again, the film appeared to have formed quicker during the higher chemical dosage experiment.

By comparing Figures 10, 11, 12, and 13, it appears that none of the lead concentration values had reached a minimum. The decreasing values indicated that the protective film had not been completely formed by the end of the fifth cycle. [The lead concentrations after adding 1.5 mg/L of ZOP 939 are well below the proposed 10 ppb lead MCL.] The lead concentrations of the fifth cycle samples from the lead/tin loop with 0.5 mg/L dosages are 11 ppm and 12 ppm lead for the 6- and 16-hr retention time, respectively. Since the lead values were still declining, it was assumed that further cycles would have yielded lead concentrations below 10 ppb.

Rend Lake Water With BMP 937

Experiments nine and ten were conducted using BMP 937, a bimetallic zinc orthophosphate, at concentrations of 0.5 mg/L and 1.5 mg/L, respectively. BMP 937 protects plumbing material from corrosion by forming a protective film on the exposed surface area. In addition to corrosion inhibition, BMP 937 contains an iron and magnesium sequestering agent.
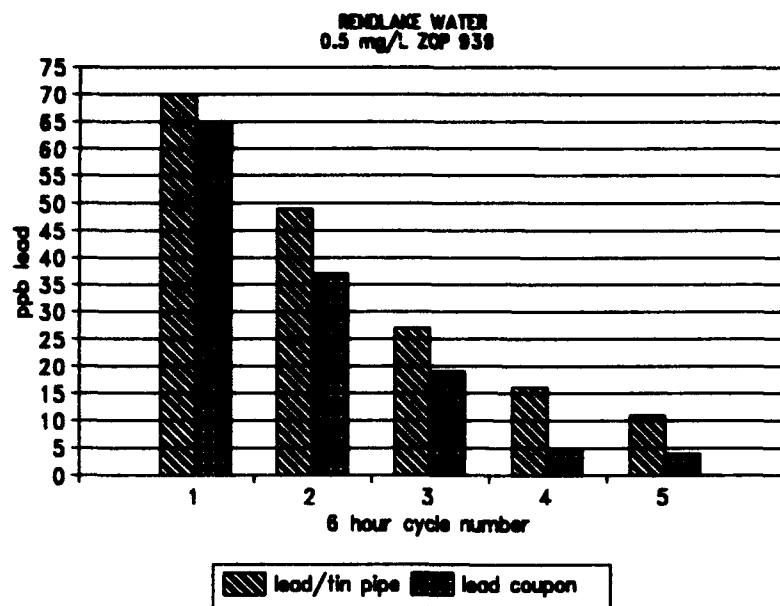
Figure 10. Lead Concentration of Samples With 0.5 mg/L ZOP 939 and a 6-hr Retention Time.
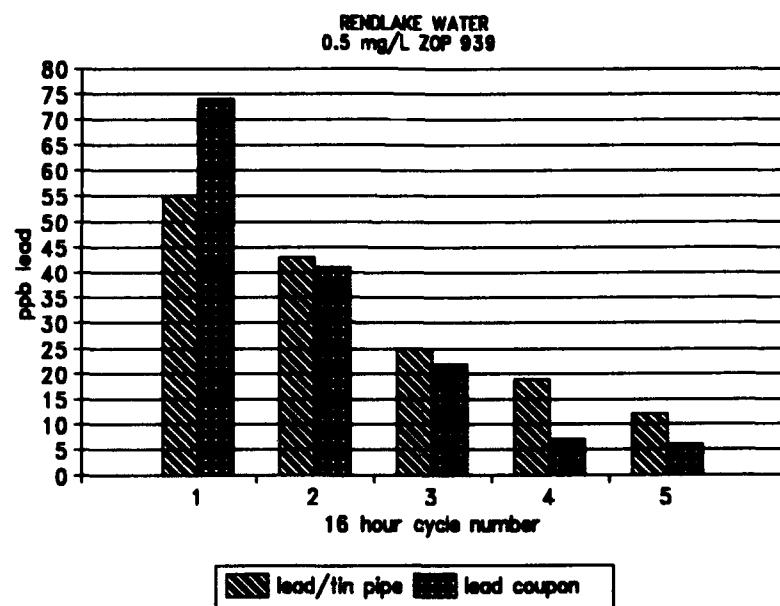

Figure 11. Lead Concentration of Samples With 0.5 mg/L ZOP 939 and a 16-hr Retention Time.
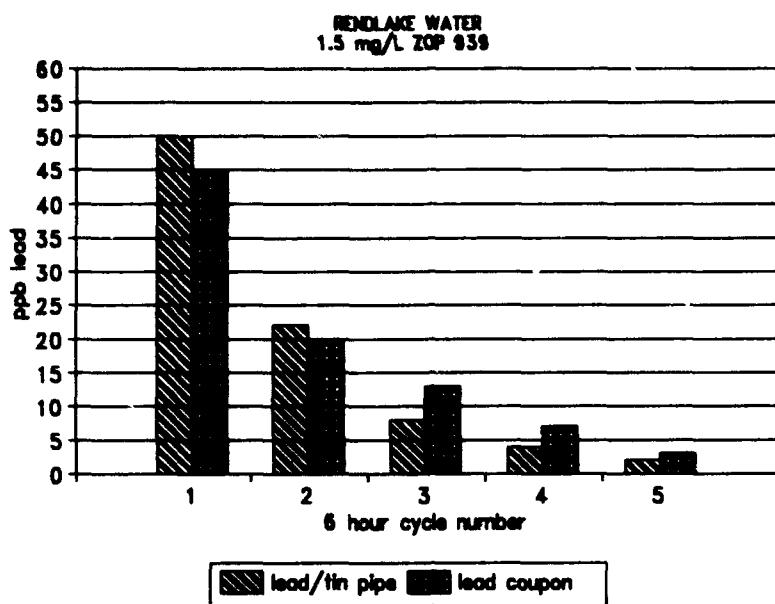
**Figure 12. Lead Concentration of Samples With 1.5 mg/L ZOP 939 and a 6-hr Retention Time.**
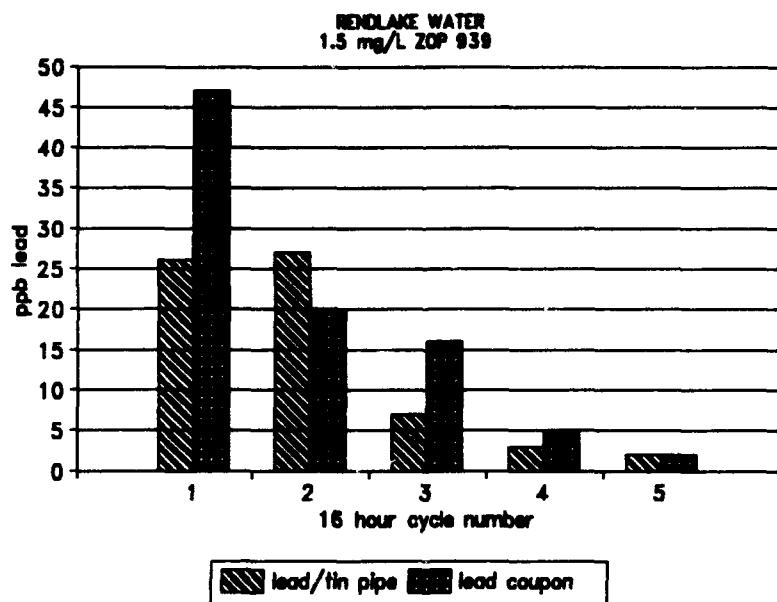
Figure 13. Lead Concentration of Samples With 1.5 mg/L ZOP 939 and a 16-hr Retention Time.

The data generated during experiment nine using 0.5 mg/L BMP 937 are shown in Figures 14 and 15 for the retention time of 6 and 16 hr, respectively. Figures 16 and 17 present the results from experiment ten using 1.5 mg/L BMP 937 for the retention times of 6 and 16 hr, respectively. The initial lead concentrations from both experiments were moderately high compared to the lead values obtained from experiment one, which did not have any chemical addition. However, after adding BMP 937, a steady decrease in lead concentration occurred throughout the experiments. Although when the fourth and fifth cycle values of all four graphs are examined, a leveling off of lead values is apparent. This indicated that a protective film had been formed and had probably reached its maximum effectiveness.

The increased BMP 937 concentration does not seem to result in a marked increase in corrosion inhibition. The small decrease in lead concentration indicated that the increased inhibitor dose was too small and a greater dose would be required to bring the fifth cycle values into compliance with the proposed 10 ppb MCL for lead. BMP 937 would not be an economical choice for a chemical corrosion control method since its effectiveness at low concentrations would not provide adequate corrosion protection.

Rend Lake Water With ZOP 931

The effectiveness of ZOP 931 for corrosion control was studied during experiments eleven and twelve. Figure 18 depicts the results of the study using ZOP 931 with a 6-hr retention time and a concentration of 0.5 mg/L. The graph indicates extremely high initial concentrations of lead. This suggests that the protective film was not formed immediately at this concentration. The lead concentration values of the fifth cycle were lower, but did not approach the compliance levels of 10 ppb, which indicates that the protective film was inadequate. Figure 19 shows the results of the same study but with a retention time of 16 hr. The graph indicates slow formation of the film at this concentration. The fifth cycle values for both loops at both the 6- and 16-hr retention periods were all above the proposed MCL for lead. The lead concentration values had reached a constant level except for the lead/tin loop at the 6-hour retention time.

Figures 20 and 21 graphically depict the results of experiment twelve, which used an increased concentration of ZOP 931 of 1.5 mg/L. The increased concentration helped the film formation as indicated by the lower initial values of lead concentration. The increased chemical dosage also lowered the fifth cycle lead values for both retention periods. The values were still above 10 ppb and appeared to have reached a consistent lead concentration of approximately 14 ppb for the lead/tin loop and 12 ppb for the lead coupon loop. The consistent values indicated that the film had reached its maximum protection level.

The dramatic lowering of the lead concentration values resulting from the increased ZOP 931 dosage indicated that ZOP 931 could be used to bring the corrosion into compliance if an even greater dosage was used.

Phase Two: Extended Cycle Studies

After analyzing the data generated from phase one, three questions arose: (1) Did the practice of conducting the experiments for a predetermined five cycles correctly indicate the effectiveness of the chemicals being tested? (2) Was there any contamination of the samples collected from the lead coupon loop due to the arrangement of the loops in a series? (3) Would the lead concentrations continue to decrease without adding any chemical corrosion inhibitors due to the formation of a carbonate scale? To answer the first question, researchers initiated an extended cycle study in which the cycles were continued until the lead levels reached a constant value. The extended cycle study used ZOP 939 at a dosage of 1.5 mg/L, since it demonstrated the quickest film formation and its fifth cycle lead concentrations were still decreasing in the previous study. The second question was investigated by using the loops separately. The third question was investigated by conducting an extended cycle study without any chemical addition.

REND LAKE WATER
0.5 mg/L ZOP 937
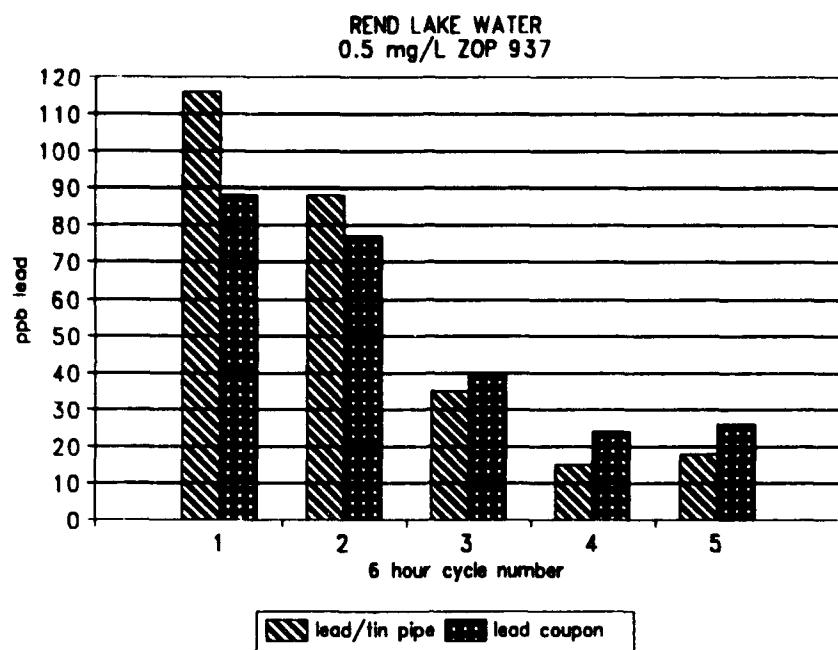
Figure 14. Lead Concentration of Samples With 0.5 mg/L ZOP 937 and a 6-hr Retention Time.

REND LAKE WATER
0.5 mg/L ZOP 937
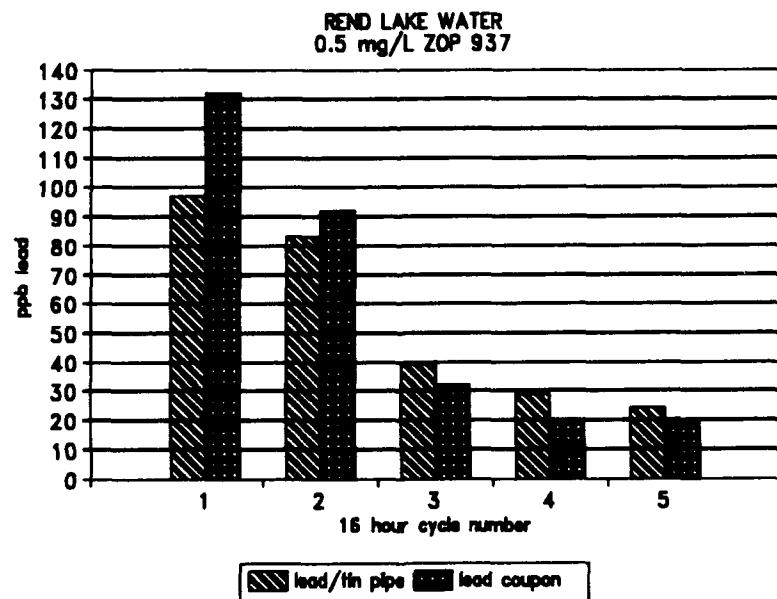
Figure 15. Lead Concentration of Samples With 0.5 mg/L ZOP 937 and a 16-hr Retention Time.

40
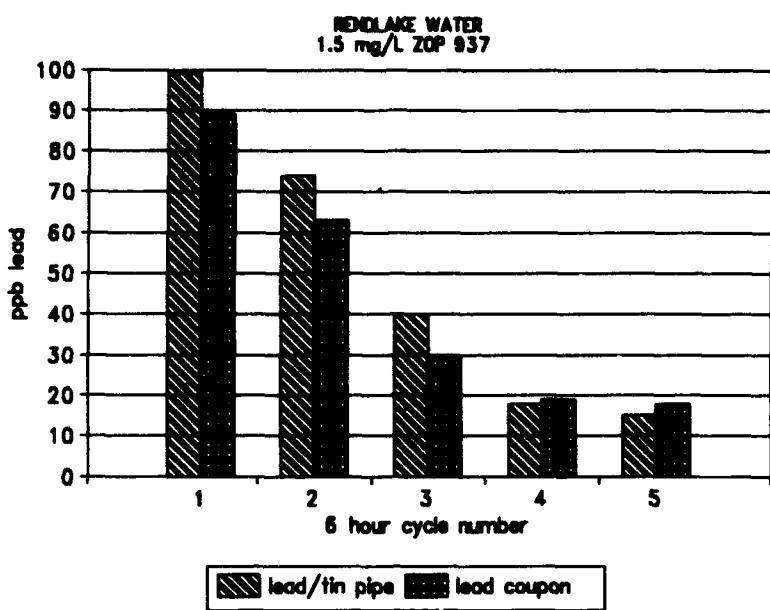
Figure 16. Lead Concentration of Samples With 1.5 mg/L ZOP 937 and a 6-hr Retention Time.
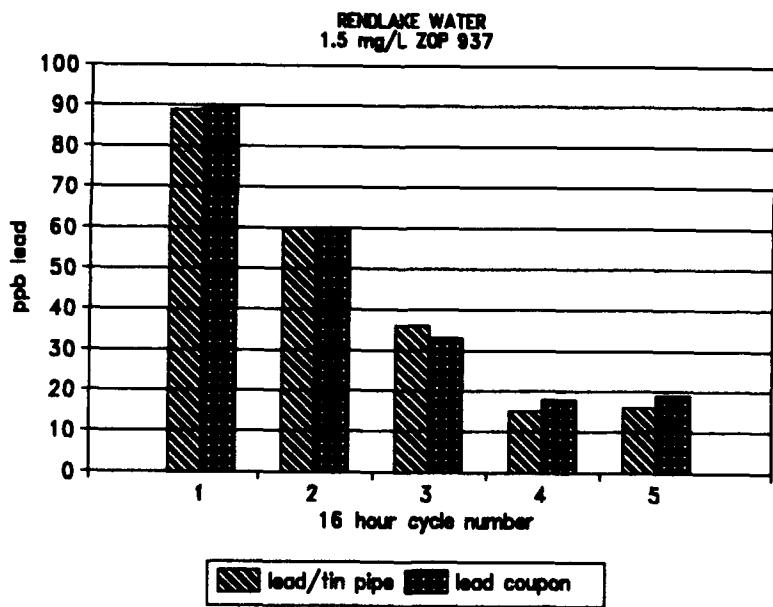

Figure 17. Lead Concentration of Samples With 1.5 mg/L ZOP 937 and a 16-hr Retention Time.

41
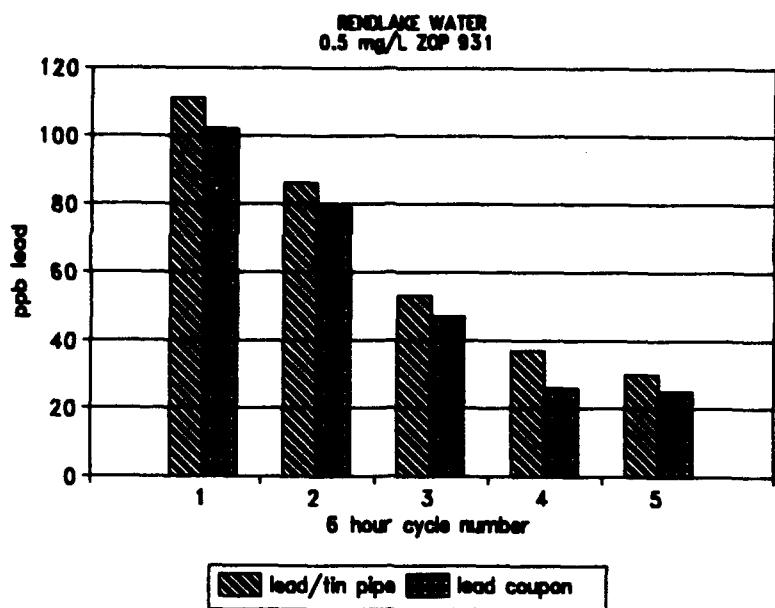
Figure 18. Lead Concentration of Samples With 0.5 mg/L ZOP 931 and a 6-hr Retention Time.
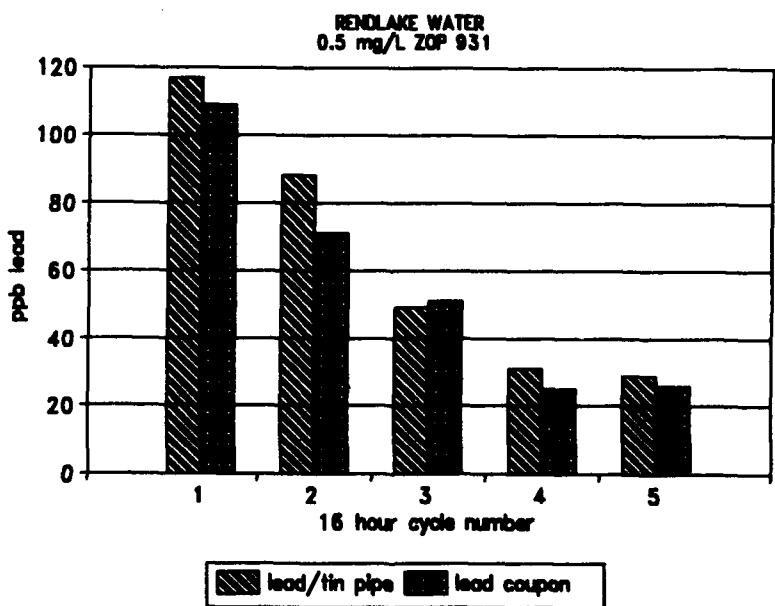
Figure 19. Lead Concentration of Samples With 0.5 mg/L ZOP 931 and a 16-hr Retention Time.
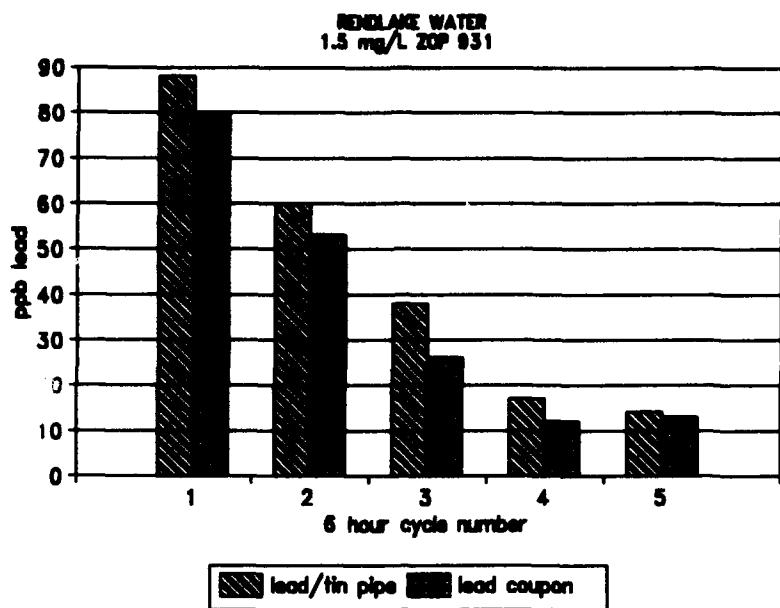
Figure 20. Lead Concentration of Samples With 1.5 mg/L ZOP 931 and a 6-hr Retention Time.
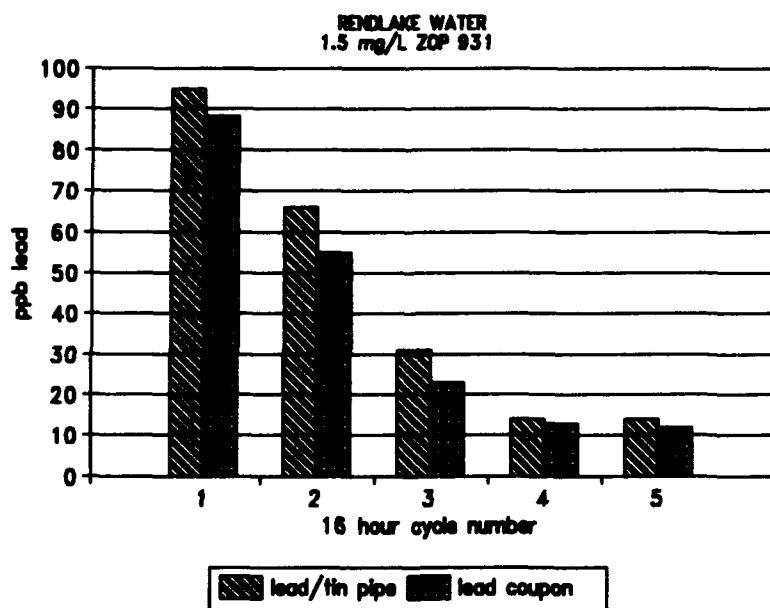
Figure 21. Lead Concentration of Samples With 1.5 mg/L ZOP 931 and a 16-hr Retention Time.

43

Since only two 50-gal tanks were used, it was impossible to supply the volume of water needed to conduct experiments with the two loops connected to the pump and tanks in parallel. For the extended cycle study of ZOP 939, two separate experiments were conducted. During the first experiment the lead/tin loop was connected to the tanks. The lead coupon loop was directly connected to the mainline distribution tap. The arrangement eliminated the possibility of cross contamination since the tanks were no longer connected. At the end of the first experiment, the arrangement of the loops was switched. During the second experiment, the lead/tin loop was directly connected to the mainline tap. The lead coupon loop was connected to the pump that supplied water with the addition of ZOP 939.

Extended Cycle Study of 1.5 mg/L ZOP 939

ZOP 939 was chosen for the extended cycle study since it showed the most promising corrosion protection. From the previous studies of ZOP 939, researchers determined that the protective film had formed rapidly but may not have been completed at the end of the fifth cycle.

The equipment setup made it necessary to combine the results from the lead/tin loop during experiment one with the results of the lead coupon loop from experiment two to construct Figures 22 and 23, which represent the 6- and 16-hr retention times, respectively. It is again evident from both graphs that 1.5 mg/L ZOP 939 forms a protective film before the completion of the third cycle of both loops. In fact, complete compliance with the proposed 10 ppb MCL was achieved during the fourth cycle of both loops at both retention times.

Figures 22 and 23 indicate that maximum protection had been achieved by the seventh cycle for the lead/tin loop and the fifth cycle for the lead coupon loop. The level of protection remained fairly constant through the ninth cycle, therefore, the experiment was terminated. The ninth cycle lead concentrations for both loops during both retention times was 2 ppb. The lead values indicated that 1.5 mg/L ZOP 939 had formed a protective film on the exposed metal surfaces that adequately prevented the corrosion process from occurring.

Extended Cycle Study Without Corrosion Inhibitors

As stated in the previous section, it was necessary to combine the results of the two extended cycle experiments to construct the desired graphs. The results obtained from the 6-hr retention period of the lead/tin loop during the second experiment were combined with the 6-hr retention period results from the lead coupon loop collected during the first experiment to construct Figure 24. Likewise, Figure 25 was completed by combining the 16-hr retention period results of the lead/tin loop from the second experiment with the 16-hr retention period data from the lead coupon loop generated during the first experiment. The combined chemical results allowed Figures 24 and 25 to be analyzed to determine the corrosive tendency of Rend Lake tap water without adding a chemical corrosion inhibitor.

The initial high lead concentrations depicted in Figures 24 and 25 for both loops and both retention periods correlated with the initial values obtained during the previous no-treatment study. The comparison reaffirms the corrosive tendency of the water. However, the corrosive action of the water diminished slightly through the fifth cycle for the lead/tin loop and the sixth cycle for the lead coupon loop. Since no inhibitor was added, the decrease was credited to the formation of a carbonate scale. The scale formation was expected since a positive LI was maintained during the experiments.

The lead concentration values appeared to have reached a minimum by the fifth and sixth cycles for the lead/tin loop and the lead coupon loop, respectively. Because the values remained fairly constant from the fifth cycle through the ninth cycle, the experiment was halted. The apparent maximum protection that had been achieved due to scale formation was not adequate enough to achieve the minimum desired 10 ppb lead concentration. The minimum values achieved from the lead/tin loop were still in excess of 30 ppb lead while the lead coupon loop was above 50 ppb lead. The high values confirmed the results
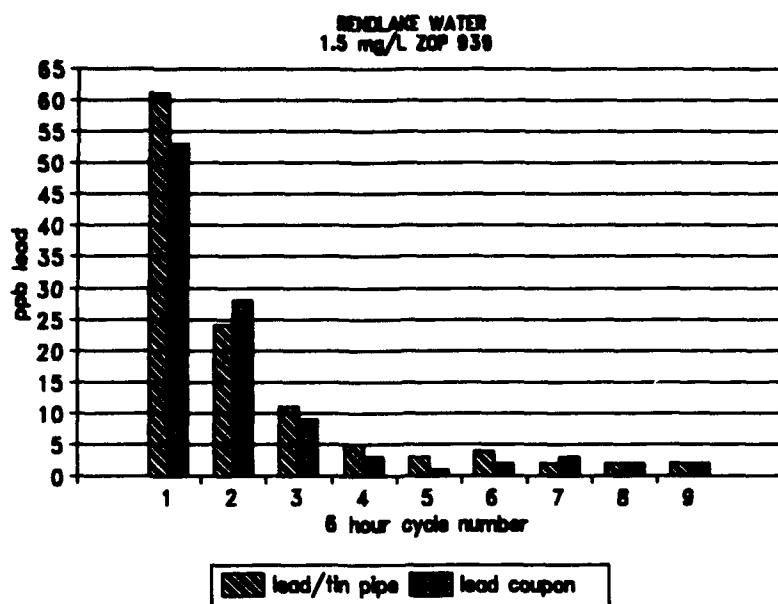
Figure 22. Lead Concentration of Extended Cycle Samples With 1.5 mg/L ZOP 939 and a 6-hr Retention Time.
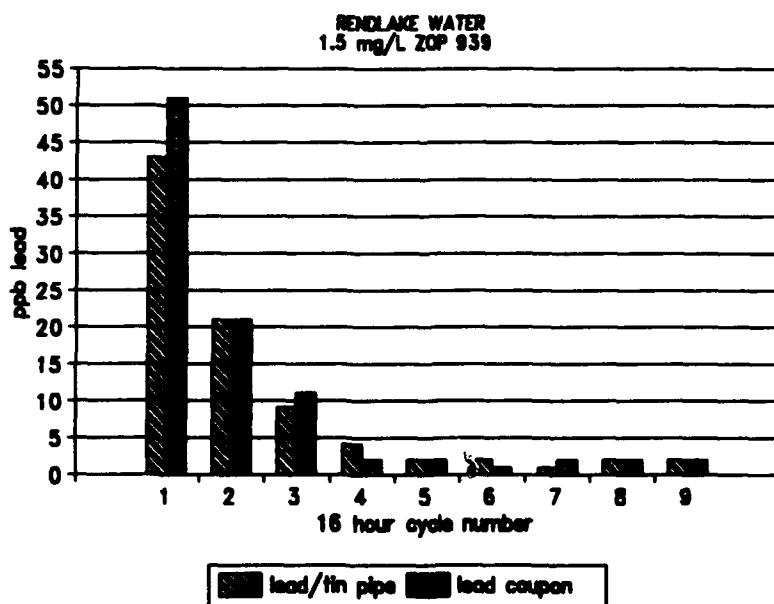

Figure 23. Lead Concentration of Extended Cycle Samples With 1.5 mg/L ZOP 939 and a 16-hr Retention Time.
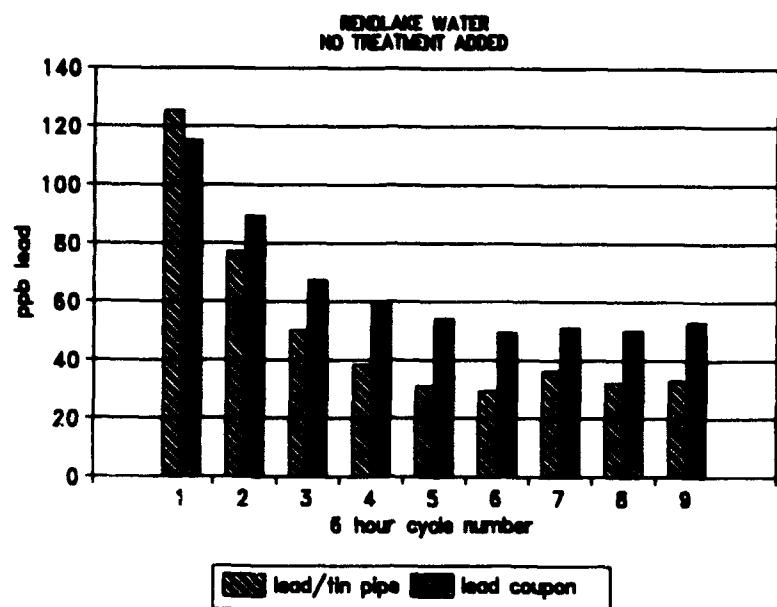
Figure 24. Lead Concentration of Extended Cycle Samples Without Chemical Corrosion Inhibitor and a 6-hr Retention Time.
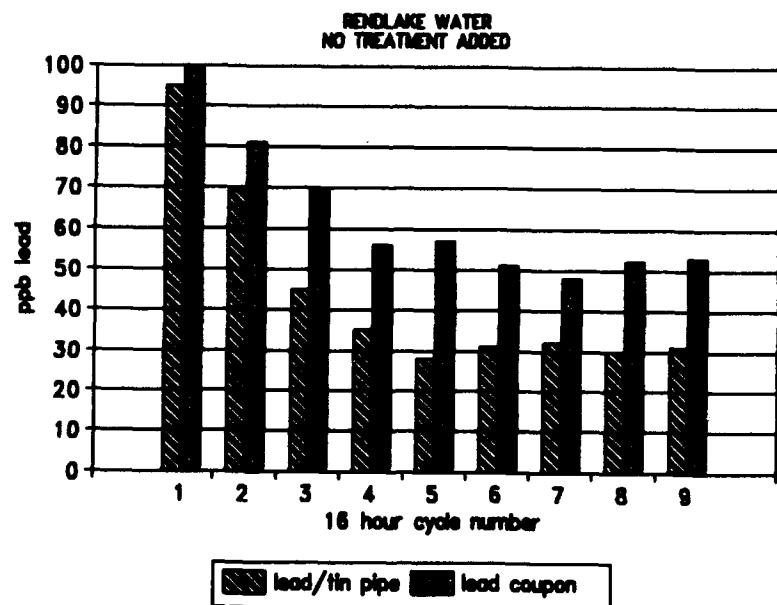

Figure 25. Lead Concentration of Extended Cycle Samples Without Chemical Corrosion Inhibitor and a 16-hr Retention Time.

of the previous study conducted without adding chemicals. The scale formation provided by maintaining a positive LI was inadequate to achieve the proposed MCL of 10 ppb lead.

Residential Water Sampling Survey

A residential water sampling survey was conducted to develop a data base that would represent the corrosion conditions of residential household plumbing systems. The data was then compared to the results obtained from the CERL-PLS during the study conducted without adding chemicals. The Rend Lake Water Conservation District water supplied to many smaller communities contains additional treatment that would alter the water quality when compared to the water used for the previous experiments. It was necessary to collect samples from a limited number of residences that were serviced directly by the Rend Lake treatment plant. Fifty such residences were contacted but only seven samples were successfully collected.

Table 6 lists the type of plumbing material used in the seven residences and the lead concentrations found in the overnight samples. The table indicates that all seven samples contained lead concentrations below the proposed MCL of 10 ppb. The lead concentration did not increase in the residences that reported copper plumbing with lead-containing solder.

Table 6

Residential Water Sampling Results

Characteristic	Residence						
	1	2	3	4	5	6	7
Age of System (yr)	22	5	10	8	12	4	16
% Copper	100	0	25	20	35	10	50
% Galvanized	0	10	25	20	50	50	20
% PVC/plastic	0	90	50	60	15	40	30
Lead Solder	yes	no	yes	yes	yes	no	yes
Lead Concentration of Sample (ppb)	2	2	1	4	5	2	7

47

5   CONCLUSIONS AND RECOMMENDATIONS

The CERL-PLS demonstrated that all four chemical inhibitors (ZOP 931, ZOP 932, ZOP 939, and BMP 937) effectively control corrosion by forming a thin protective film on exposed metal surfaces.

ZOP 939 was found to be the most effective chemical corrosion inhibitor. The CERL-PLS experiments conducted with ZOP 939 indicated that a protective film was formed within 3 days on both the lead coupons and the lead/tin pipes after treatment with 1.5 mg/L ZOP 939. The protective film brought the lead concentration of the samples below the proposed MCL for lead after only 4 days of chemical treatment. The film appeared to be effective after 5 days.

The data generated during the extended cycle experiments indicated that the use of 5-day cycles with the CERL-PLS during the first phase of the study was appropriate. The lead concentrations of the samples appeared to have been at a minimum value after the end of the fifth cycle. No significant change in lead concentration occurred from the sixth through ninth cycle. The same results were concluded from experiments with and without the presence of an inhibitor (ZOP 939) and were concluded from both the lead coupon PLS and the lead/tin PLS.

The CERL-PLS is capable of providing results of new treatment strategies without the inconvenience of gathering samples throughout the distribution system.

The great costs associated with the development and implementation of full scale corrosion treatment at Army facilities and municipalities potentially could be minimized by using the CERL-PLS. The CERL-PLS should be used to examine a variety of treatment options to ensure the most effective treatment is used.

A well-planned residential or building water sampling program could be used to show the statistical significance of using a CERL-PLS to evaluate corrosion control. The sampling program would assist the DEH/DPW in determining the corrosive nature of the product water. The optimal sampling program would target residences with the greatest potential for high lead levels. Examples of such residences include those that have lead service lines, those that use lead based solder, and new construction. Also, low risk construction using plastic plumbing should be included in future studies to allow comparison.

The CERL-PLS should be considered for use by all installations to assist in monitoring the effects of water quality on the distribution system and to assist in evaluating corrosion control alternatives. These actions can help installation water utilities meet requirements of the Safe Drinking Water Act.

METRIC CONVERSION TABLE

1 in.	=	25.4 mm
1 sq in.	=	6.452 cm^2
1 mi	=	1.61 km
1 lb	=	0.453 kg
1 gal	=	3.78 l
°F	=	(°C × 1.8) +32

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